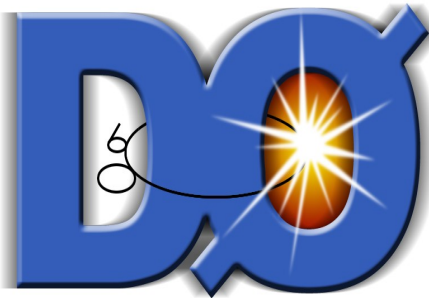


Standard Model Physics at the Tevatron



Homer Wolfe

The Ohio State University
On Behalf of the CDF & DØ
Collaborations

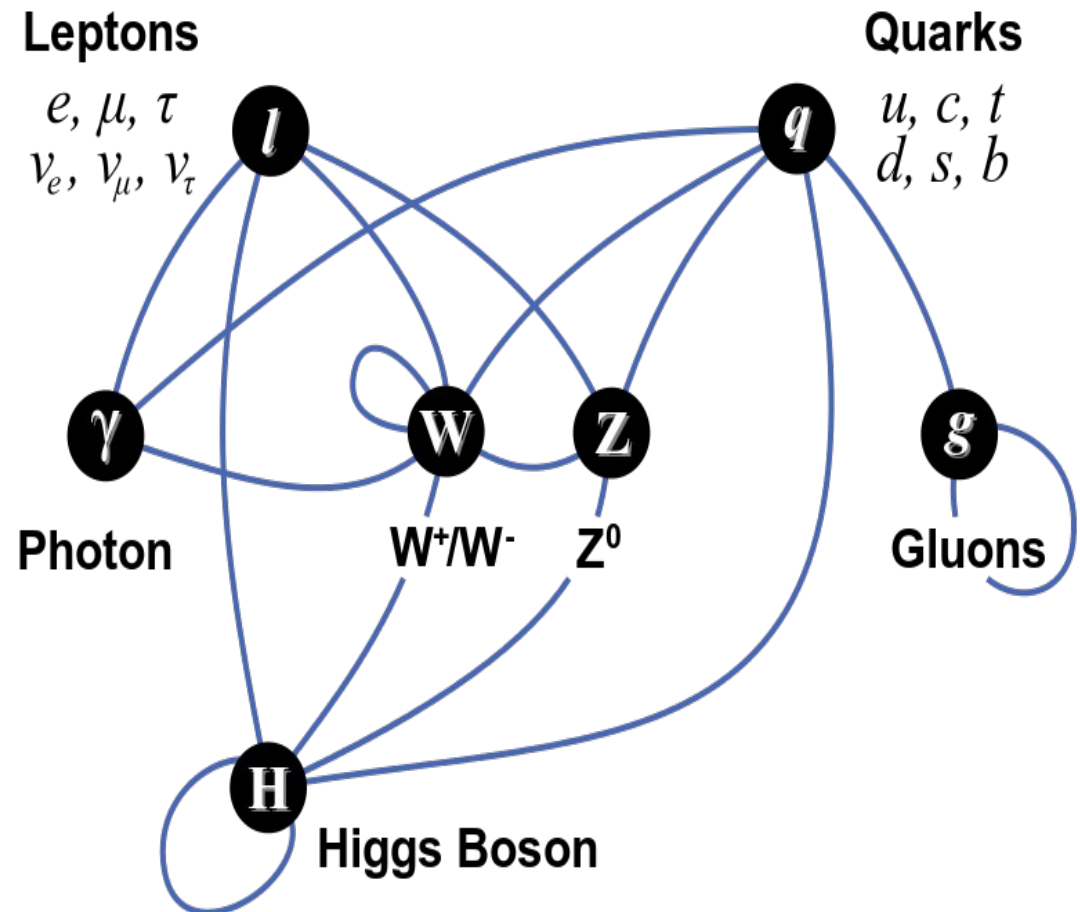


PHENO: 10 May 2011
Madison, Wisconsin

Tevatron SM Physics Goals

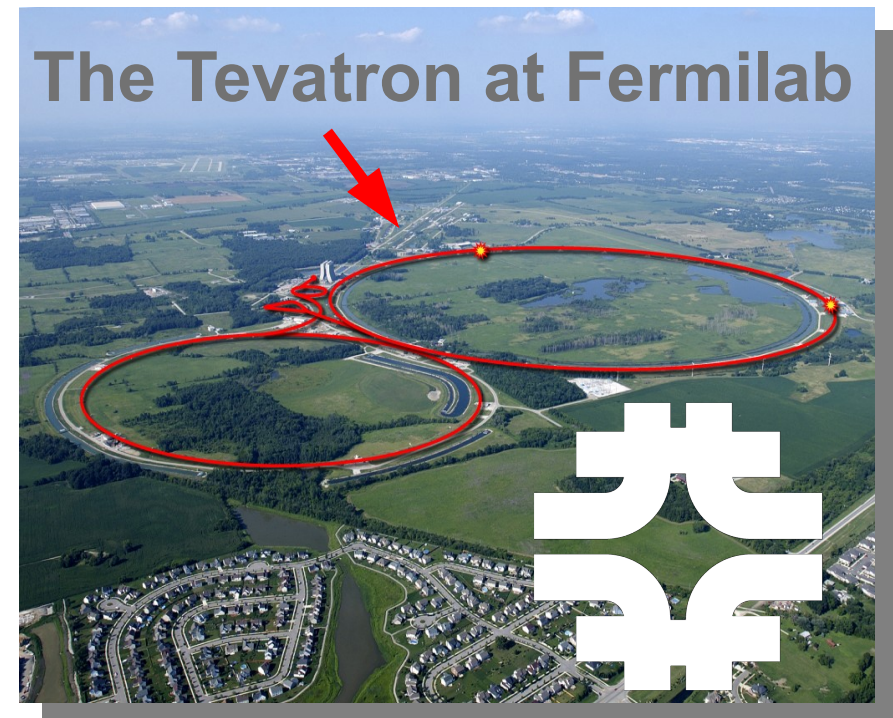
● Produce, Reconstruct SM Objects and Decay Products

- Production Rates
- Distributions, correlations
- Asymmetries
- UE/MPI
- Masses,
- Decay Widths
- Branching Fractions
- CP Violation
- Couplings
- Inputs to PDF fits
- SM Higgs Searches

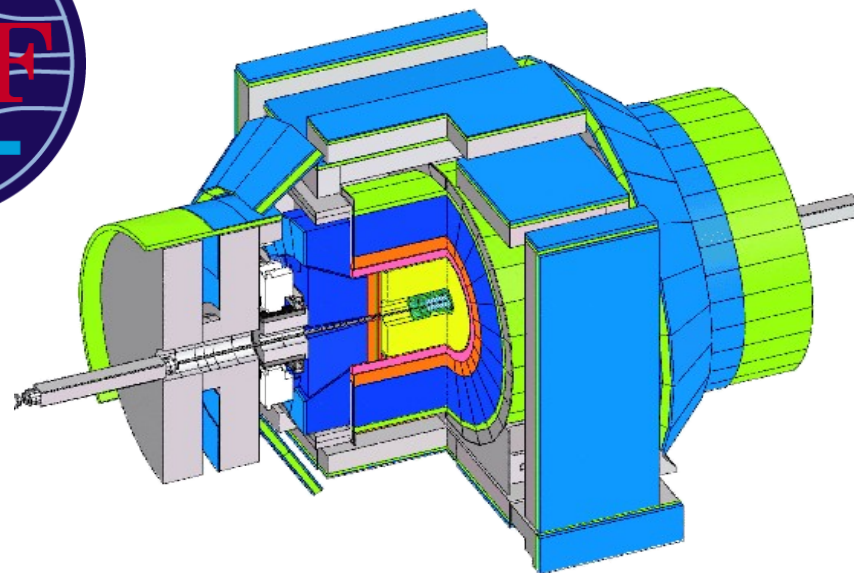
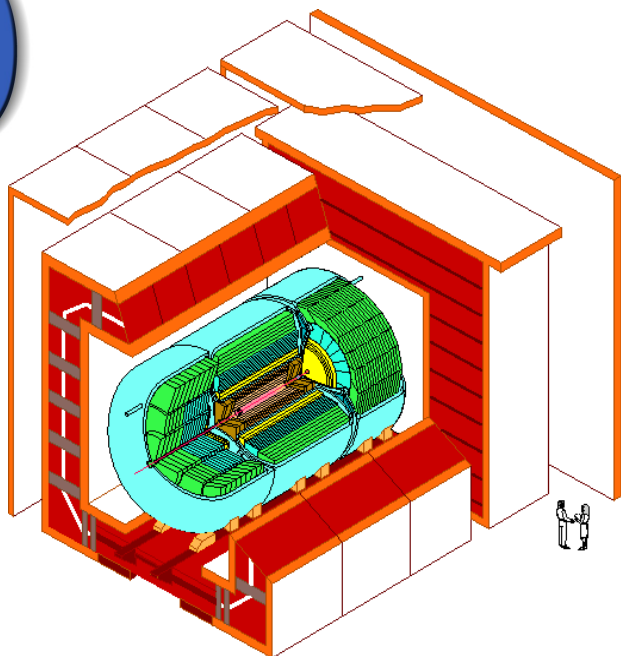


The Tevatron, Batavia IL, USA

- Superconducting Storage Ring
 - 1km Radius
- Run II: Mar 2001-Sept 2011
- Provides $p\bar{p}$ Collisions at 1.96 TeV to CDF/DØ
 - 36x36 bunches
 - $\sim E10$ - $E11$ p/bunch
 - $\sim 21\mu s$ per revolution
 - ~ 1.5 MJ beam energy
- Exemplary Performance
 - Peak inst.: $>4.2E32$ cm⁻²/s
 - ~ 70 /pb delivered/week
 - Sept: ~ 12 /fb del./exp.



Two General Purpose Detectors

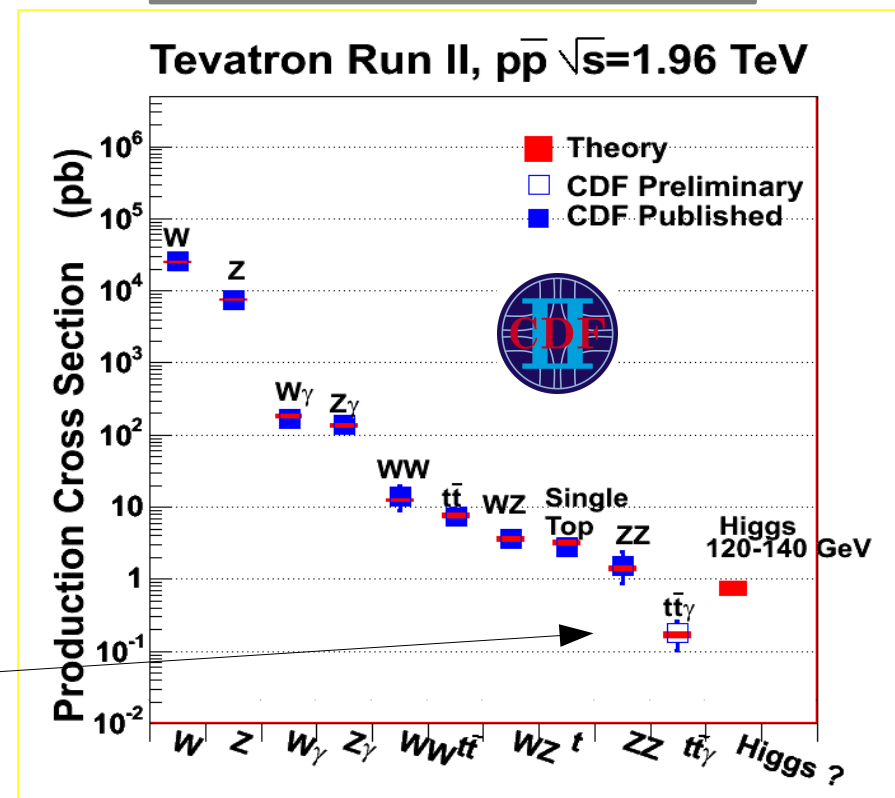
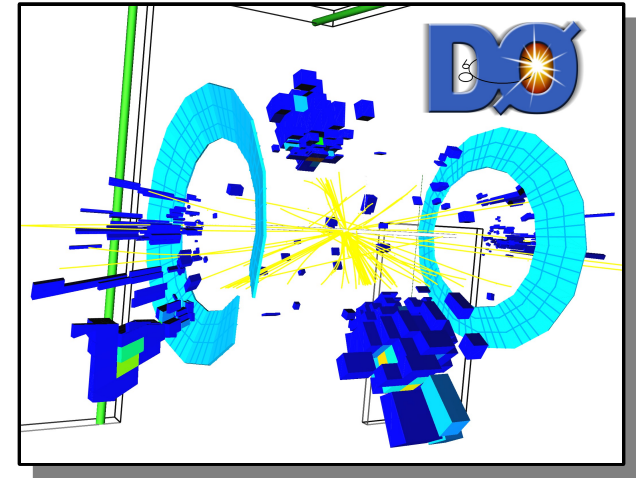


- Silicon Tracking $|\eta| < 3$
- Scintillating Fiber Tracker
1.9 Tesla B Field, $|\eta| < 1.7$
- LAr/DU Calor. $|\eta| < 4$
- Muon Chambers: $|\eta| < 2$
- JES 1-2%

- Silicon Tracking $|\eta| < 2-2.5$
- Drift cell Tracker
1.4 Tesla B Field, $|\eta| < 1.1$
- Pb/Cu/Scint Calor. $|\eta| < 3.2$
- Muon Chambers: $|\eta| < 1.5$
- JES Resolution 2-3%

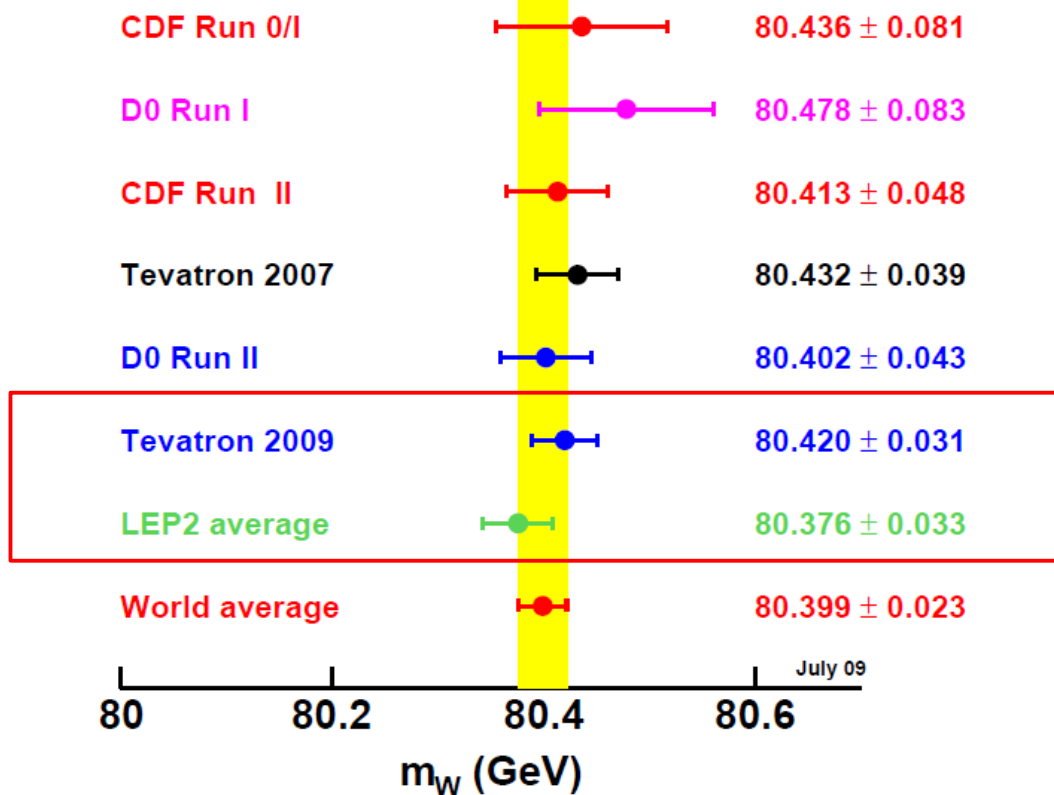
The Datasets

- **85-90% Data taking efficiency/Exp**
 - Up to 8/fb results presented here
 - >9/fb on tape today
 - >10/fb by end of program
- **Typical #vertices/event 1-3**
- **Candidates per experiment, fb⁻¹:**
 - $B^0_s \rightarrow J/\psi \phi$: ~1K-2K
 - $t\bar{t} \rightarrow e/\mu + \geq 1 \text{ b-tag}$: ~200
 - $Z \rightarrow ee/\mu\mu$: ~60K
 - $(W \rightarrow e/\mu) + \text{dijet}$: ~10K
 - >30 GeV photons : ~2M
 - $ZZ \rightarrow 4l$: ~1
 - $t\bar{t} + \gamma \rightarrow \gamma + l + \text{MET} + \text{jets}$: ~5

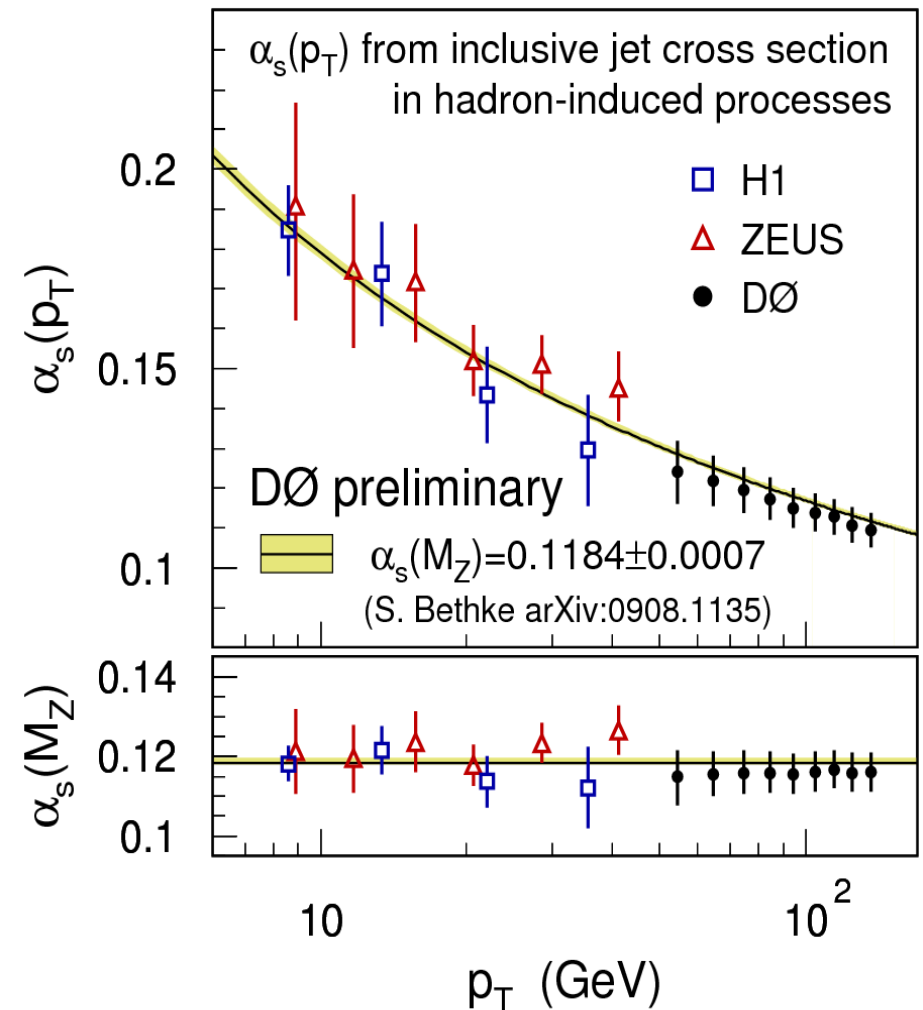


- Fundamental parameters measured
- Fundamental principles tested

2009 Tevatron W mass precision exceeds LEP2



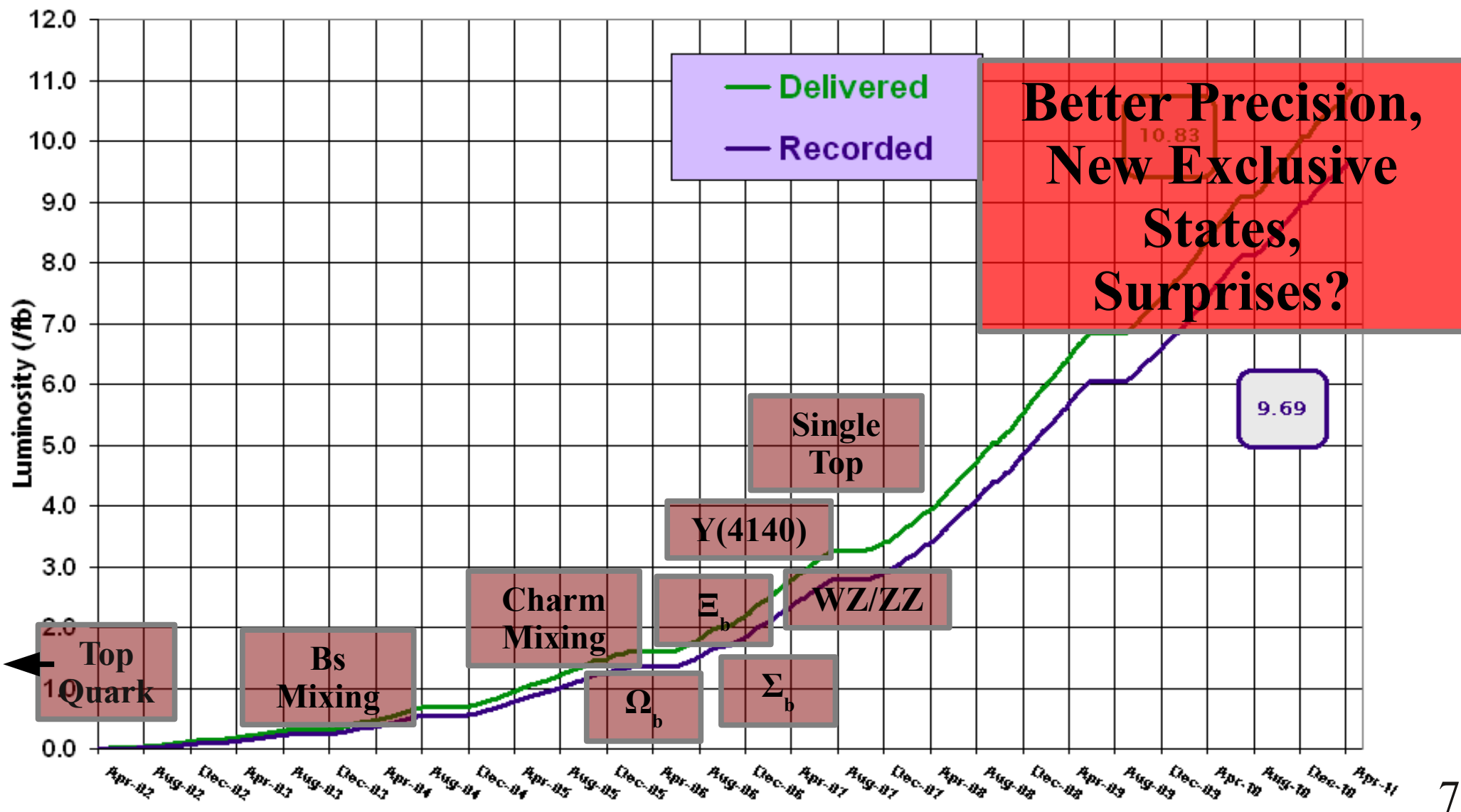
QCD Scale Evolution!





Run II Integrated Luminosity

19 April 2002 - 1 May 2011



QCD At the Tevatron

● New Measurements Presented:

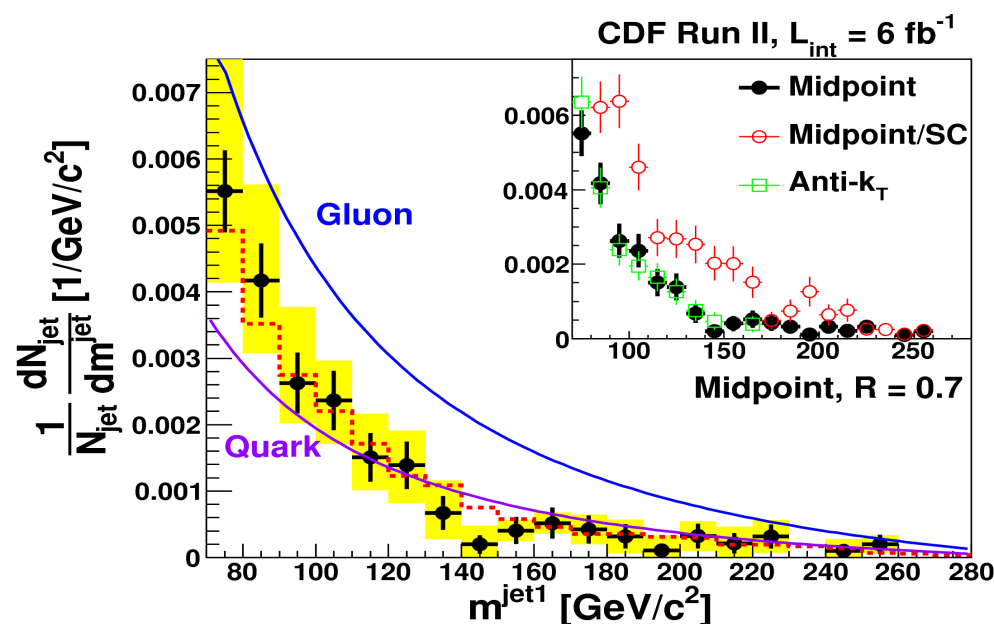
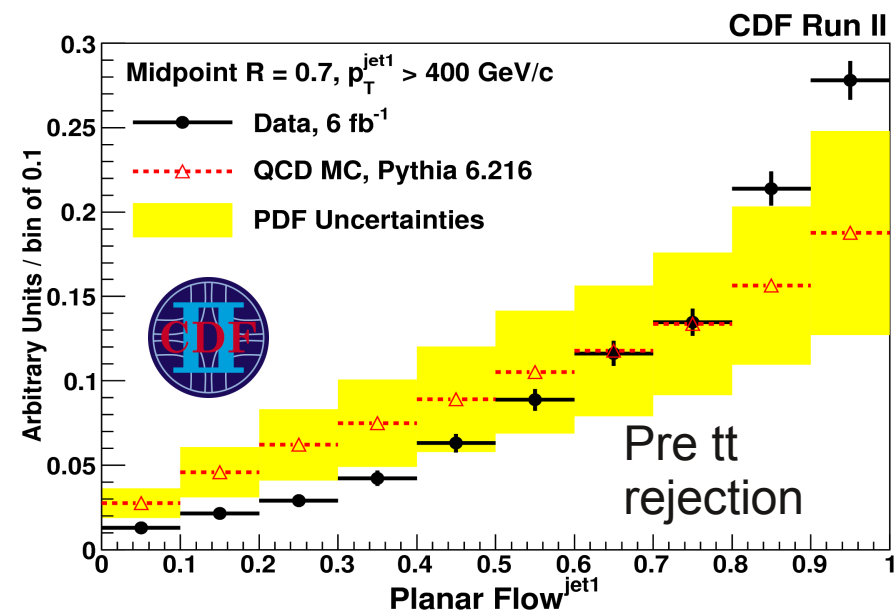
- Substructure in High-ET Jets
- 3-Jet Differential Cross Sections
- Azimuthal Decorrelations in γ +Jets

● Other great results:

- D0: Measurements of differential cross sections and angular distributions of $Z/\gamma^* + \text{jets} + X$ events
- D0: A Measurement of the Ratio of Inclusive Cross Sections $\sigma(pp \rightarrow Zb\text{jet}) / \sigma(pp/Z + \text{jet})$
- CDF: Prompt diphoton production
- CDF: Diffractive W/Z production
- CDF: Inclusive photon+heavy flavor
- CDF: Pt-Balance in Z+jets

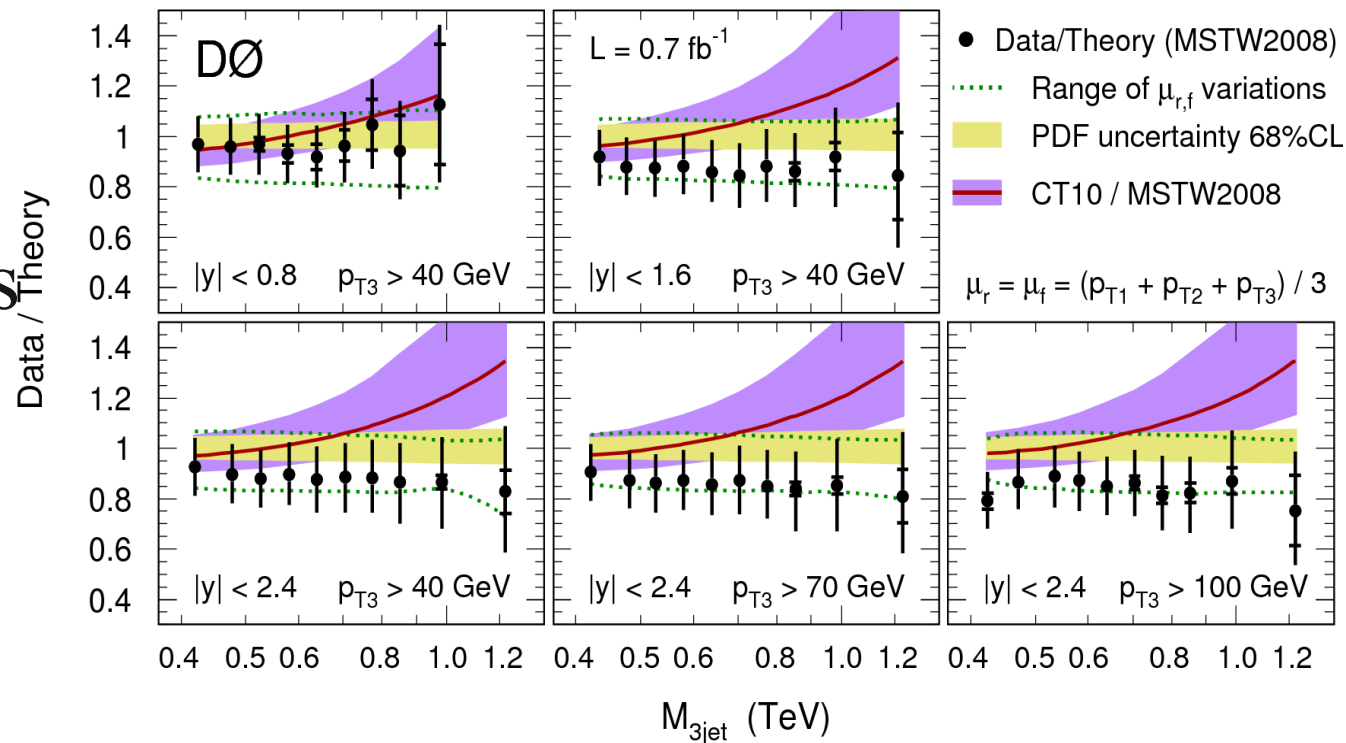
Substructure of High-ET Jets

- Some searches at the LHC will involve jet substructure
- Study model agreement of substructure of jets with **ET > 400 GeV in data**
- Remove High-ET ttbar decay jets
- Derive corrections for UE/MI
 - From unclustered energy outside jets
 - Subtract these corrections from higher vertex multiplicity
- Examine structure variables for QCD jets under multiple finding algorithms
 - Mass
 - Planar Flow
 - Thrust



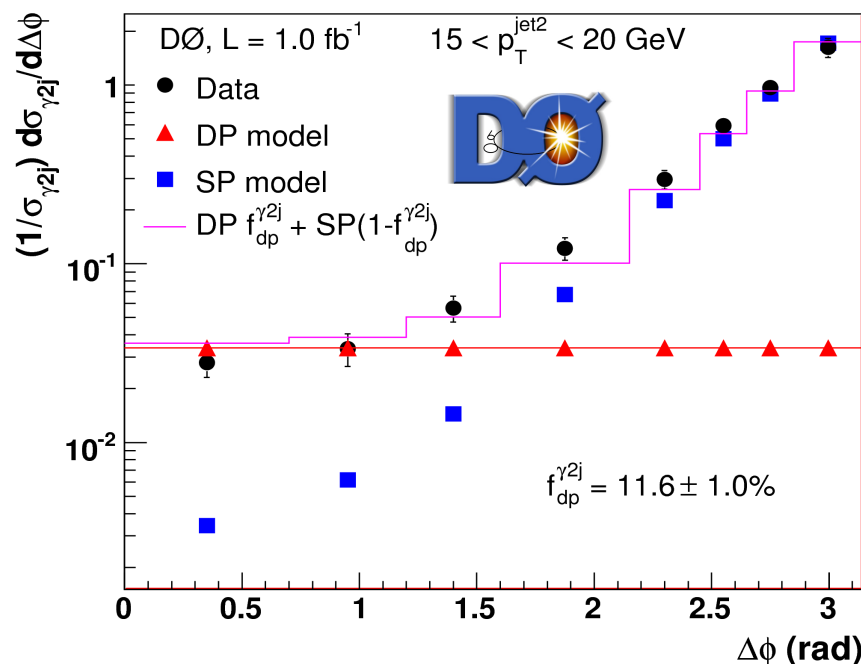
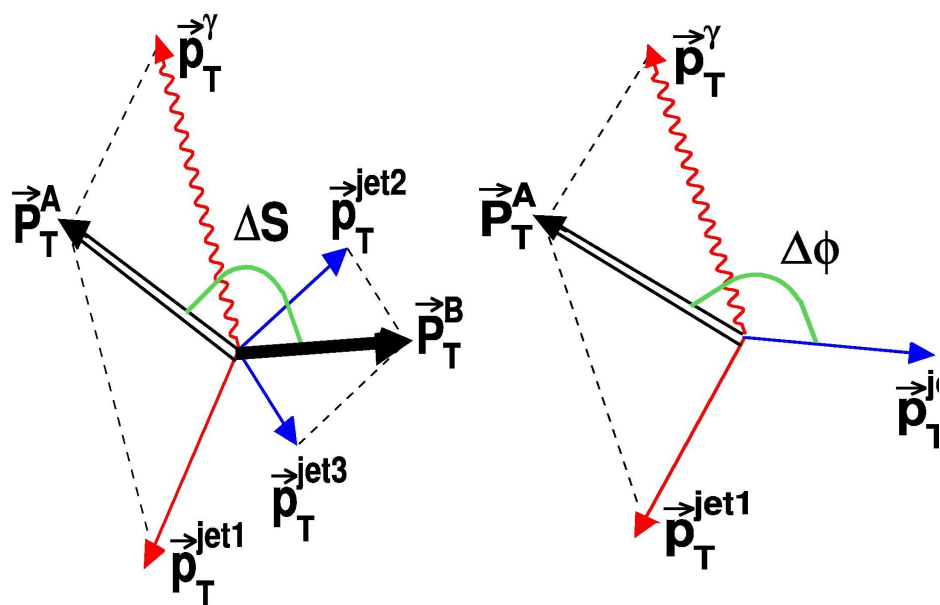
3-Jet Differential Cross Sections

- First measurement of differential 3-jet XS at Tevatron
- Corrected to parton-level with SHERPA
- Data show ability to constrain PDFs at high M_{3j}
- Comparisons to many PDF sets
NLO predictions
with simultaneous fit to α_s



Azimuthal Decorrelations and MPI in $\gamma+2/3$ jets

- Explore higher order QCD without explicit reconstruction of additional jets
- Create templates of single and multi-parton interactions to extract shapes from data.
- Can be used for tuning MC Generators



Top Physics at the Tevatron

● New Measurements Presented:

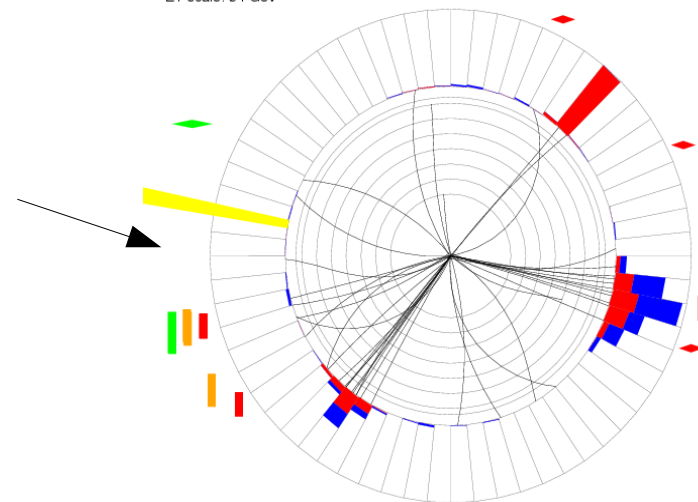
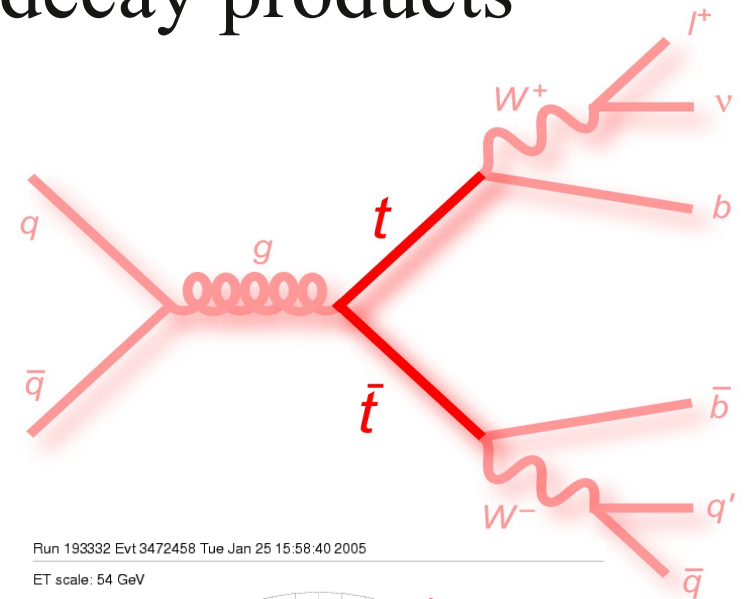
- Top Mass Combination
- Color Flow in Top Decays
- Top Quark Charge Asymmetry

● Other great results:

- Single-Top Production, V_{tb}
 - See talks by J.Joshi and Y.T.Tsai at 14:30,14:45 Today!
- Top Production Cross Sections
- W Helicity, spin correlations
- Direct Charge Measurement
- Top-antitop mass asymmetry
- Searches for New Physics With Top Decays (Next Talk)

Top Quark Pair Reconstruction

- Many top quark measurements at D0/CDF involve association of all individual top decay products
 - likelihood based kinematic fit
 - Matrix element probability
- Successes:
 - Direct measurement of t-charge
 - Soft leptons from b
 - Aggregate jet charge
 - Spin correlations in $t\bar{t} \rightarrow l\bar{l}b\bar{b}$
 - Use tagging to reduce combinatorial background



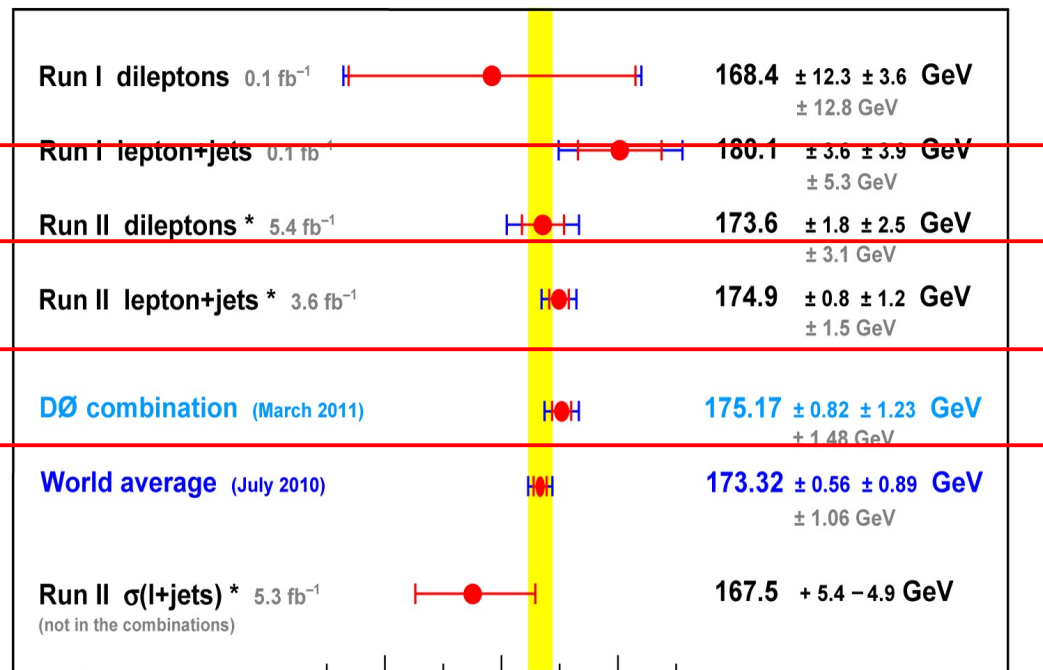
Top Mass Measurements

- New D0 and CDF combinations!
- Draw power from dilepton, semileptonic, and all hadronic decays
- Systematics dominated

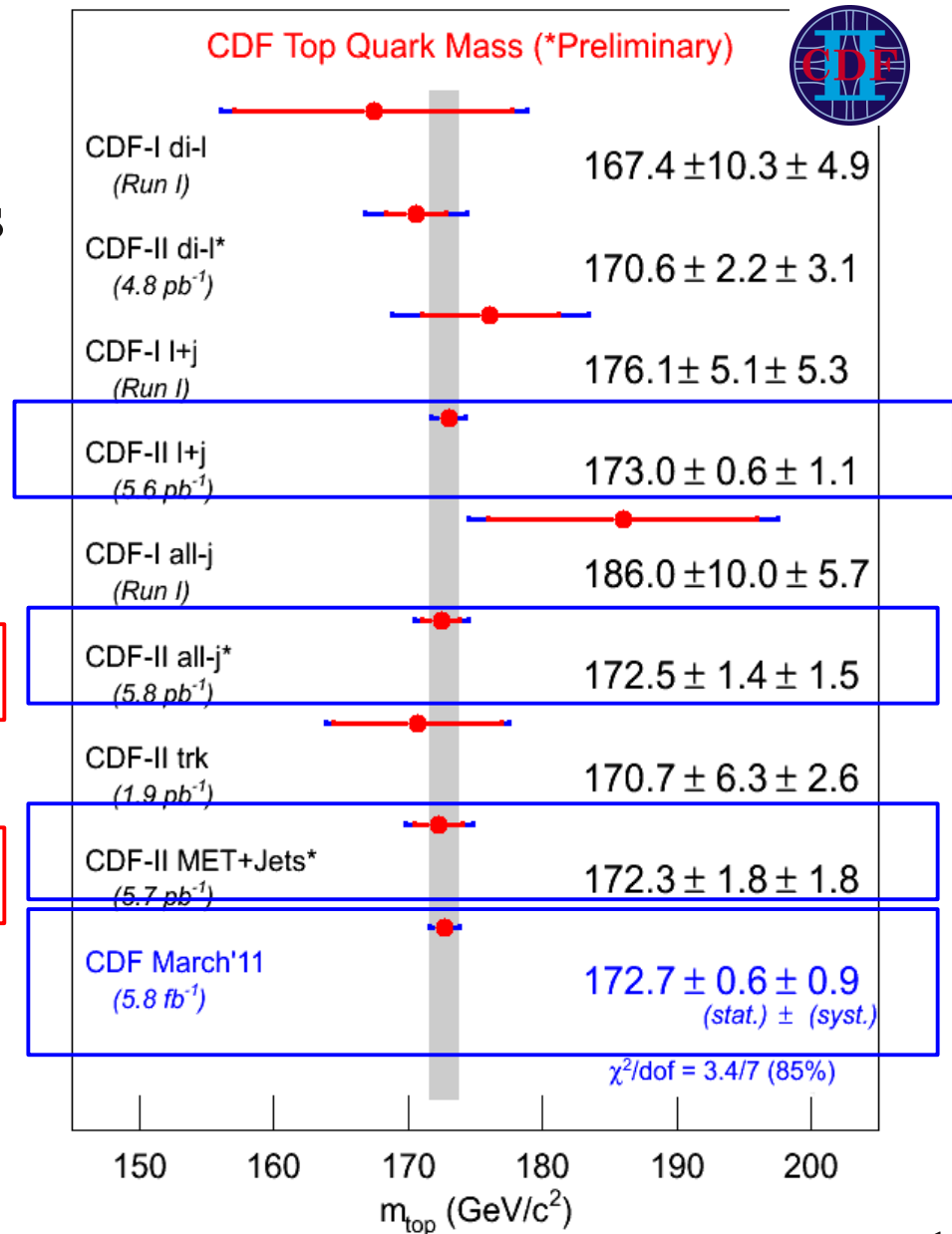
DØ - Approaching 1 GeV

* = preliminary

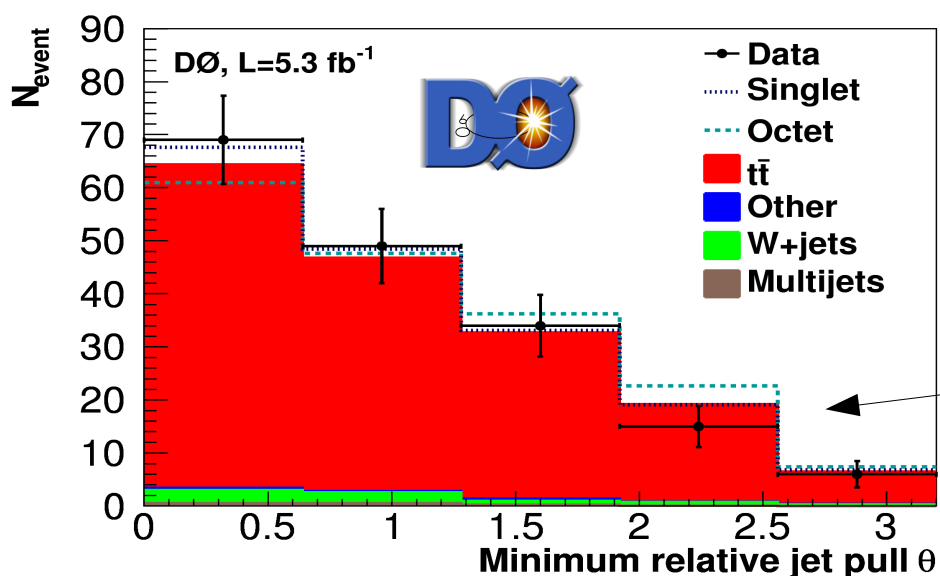
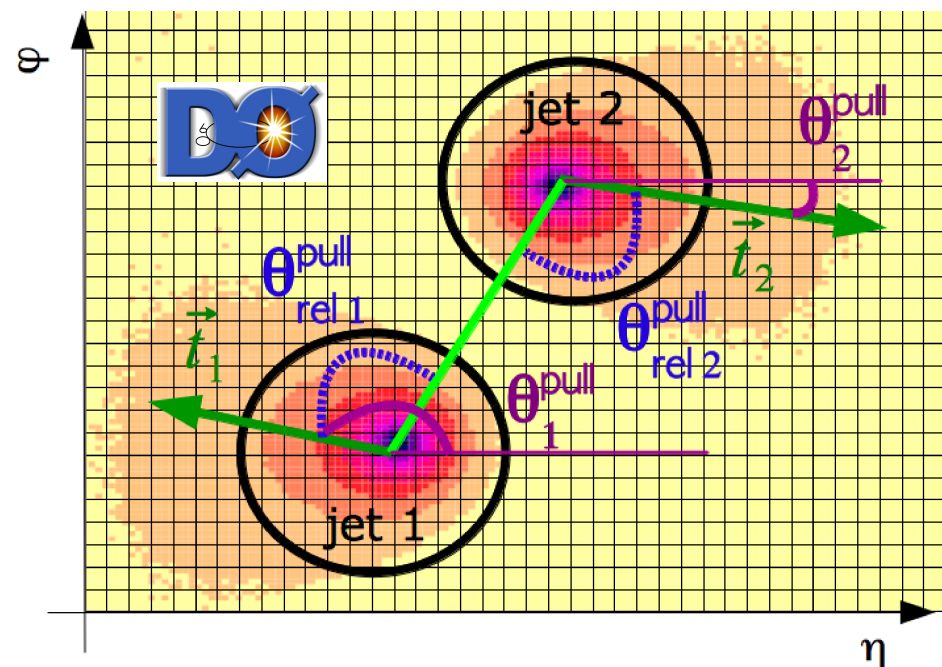
March 2011



Top Quark Mass [GeV]



Color Flow in Top Decays

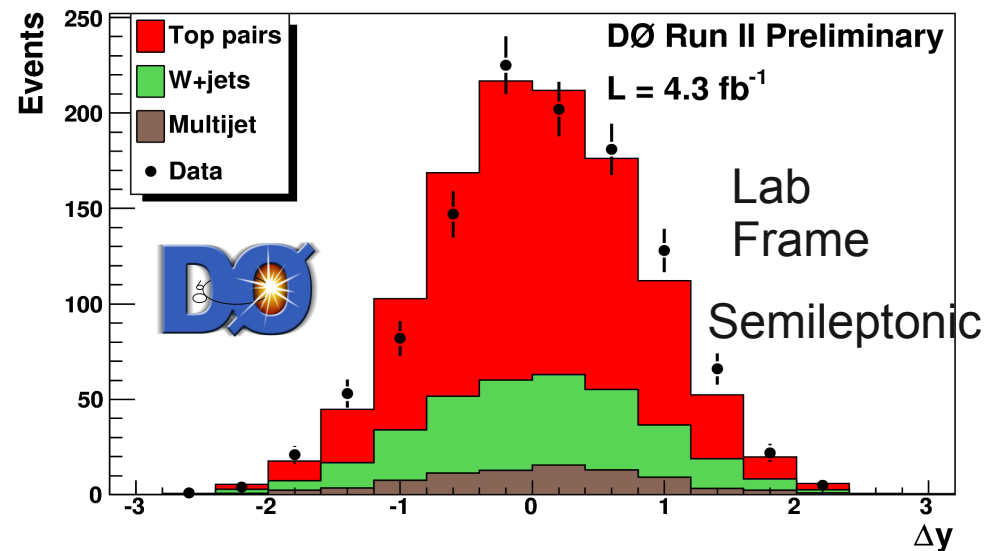
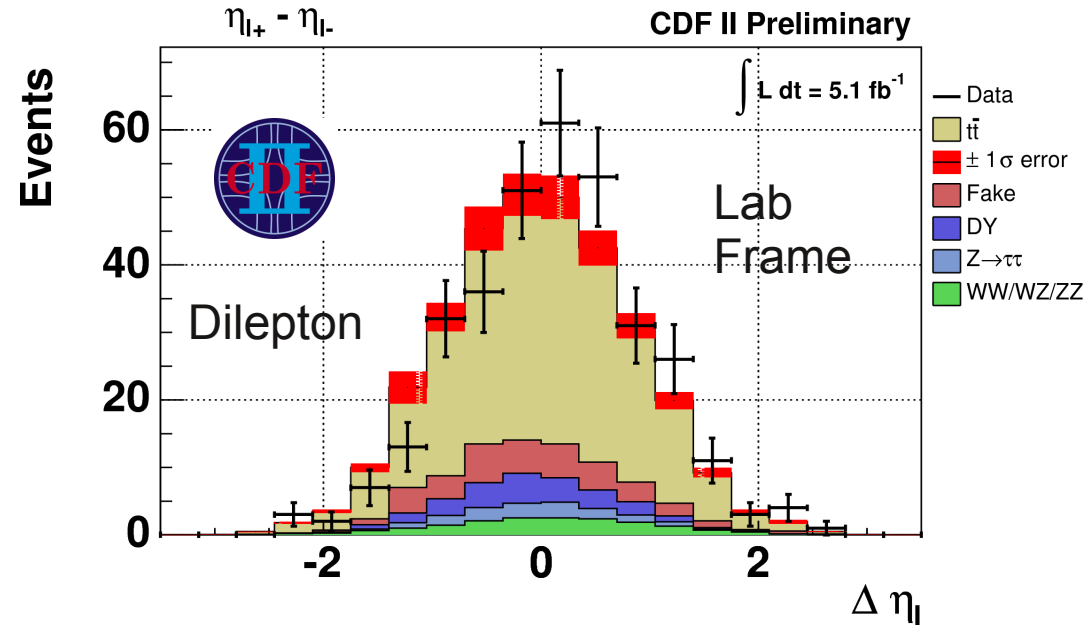
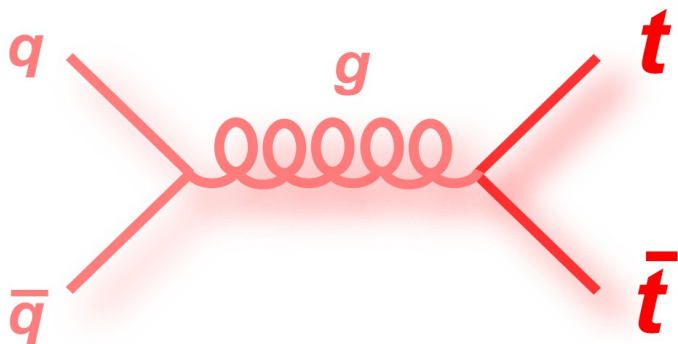


- Colorflow can be a tool to separate color-singlet-mediated processes from color octet-mediated
 - $H \rightarrow b\bar{b}$ vs QCD $b\bar{b}$
- Measure “pull” of W,t decay jets.
- W \rightarrow jets better described as color singlet than as toy “octet” model
 - %singlet contribution $> 0.277 @ 95\% \text{ CL}$

Untagged pair jets (from W),
for events passing the
MW requirement, with $\Delta R < 2$,
and $|\eta| < 1$ for both jets.

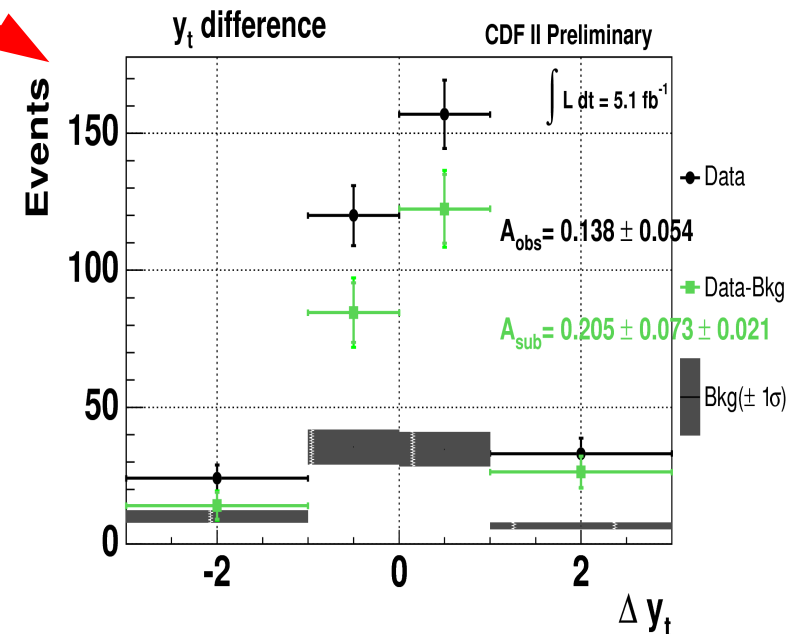
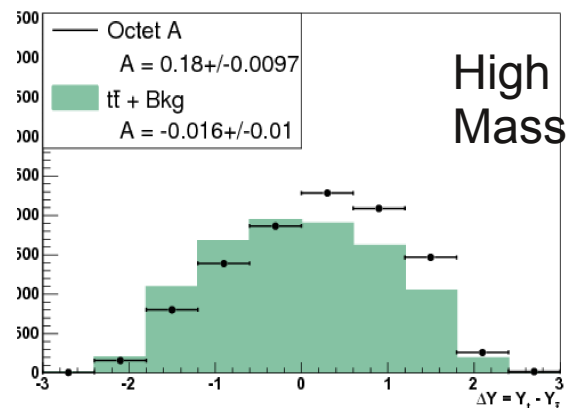
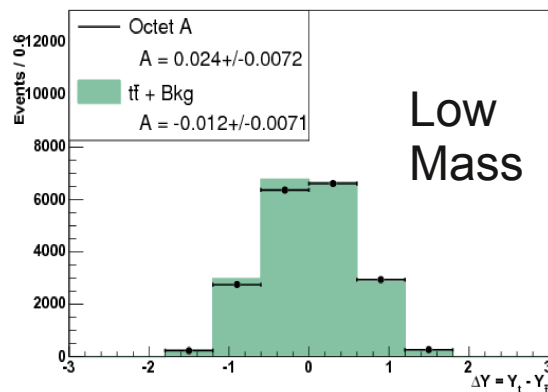
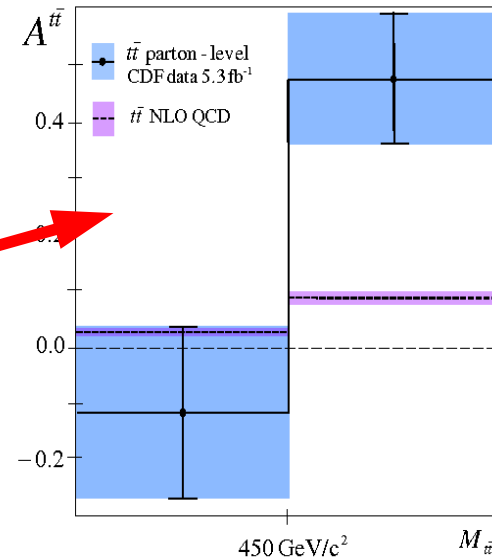
Top Quark Charge Asymmetry

- Measure signed difference of top and anti-top η
- AFB 0.088 \pm 0.013 predicted @NLO in SM
- 3-sigma higher AFB observed by CDF and D0
 - Agreement between CDF-D0 in lab frame measurement



Top Quark Charge Asymmetry

- Asymmetry is stronger in $t\bar{t}$ -rest frame
- Also Observed in CDF dilepton+jets
- CDF: High mass enhancement
- All studies statistics dominated
 - Analyses only $\sim 6/\text{fb}$



Electroweak Physics

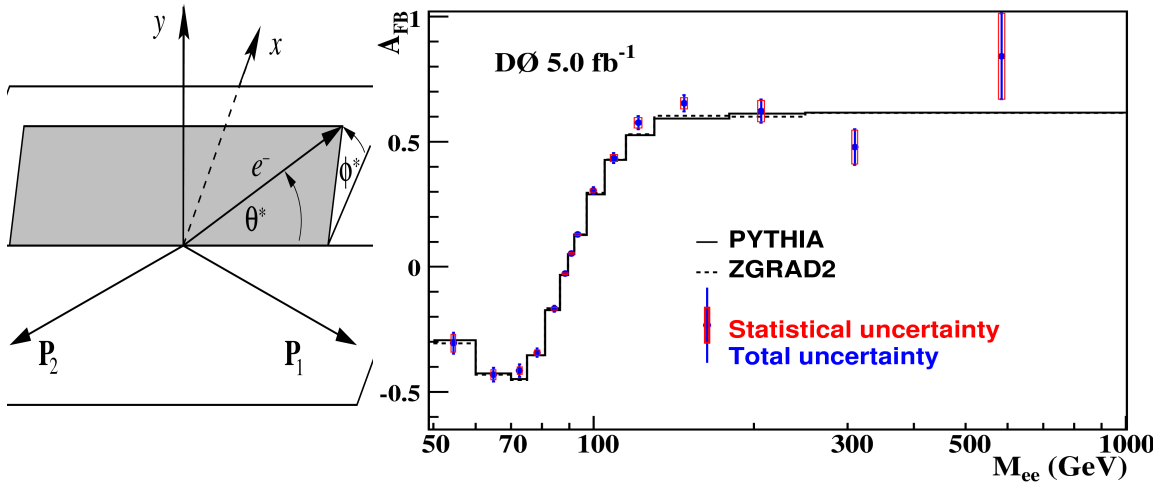
● Results Presented Here:

- $Z \rightarrow e^+e^-$ Charge Asymmetry
- $Z \rightarrow e^+e^-$ Angular Coefficients
- ZZ Cross sections (4-l and llvv)
- Wjj Invariant Mass Distribution

● Other Great Results:

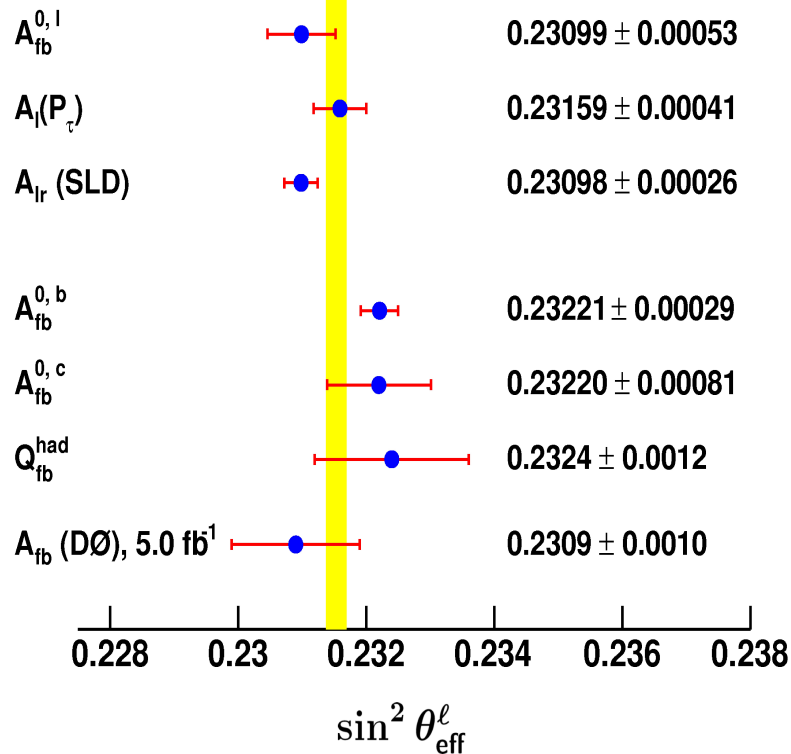
- W/Z Mass
- Precise study of the Z/γ^* boson transverse momentum distribution in $p\bar{p}$ collisions using a novel technique
- CDF/D0 Measurements of the $WZ \rightarrow l\nu ll$ cross section
- $Z+\gamma$
- Drell-Yan Differential Cross Sections

$Z \rightarrow e^+ e^-$ Charge Asymmetry



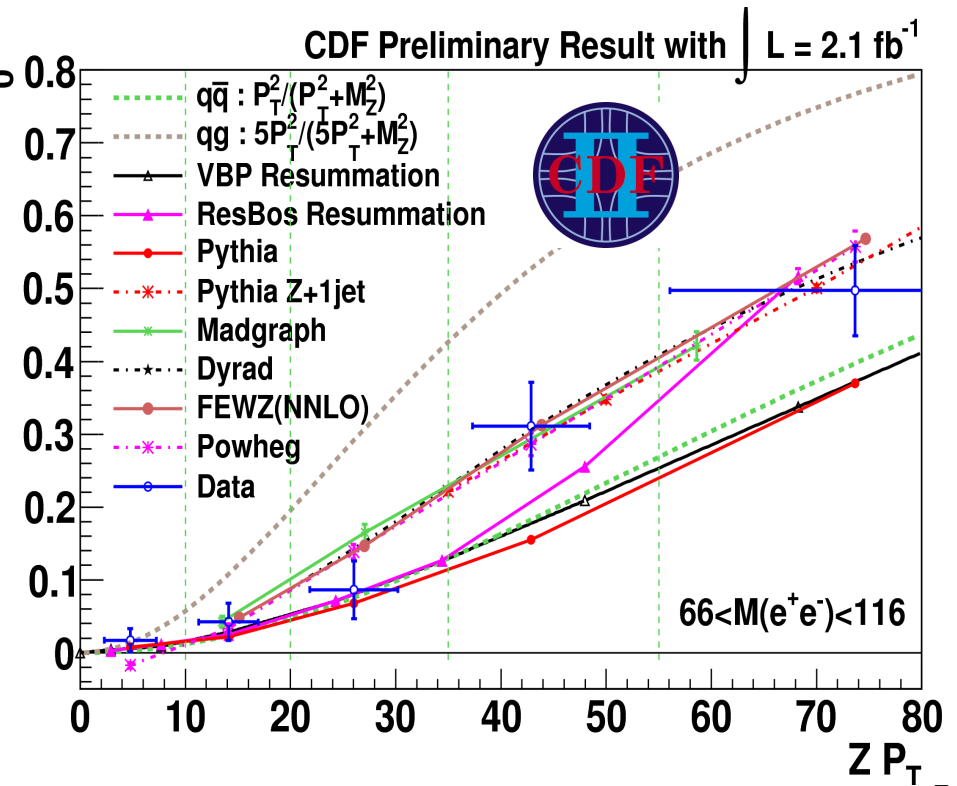
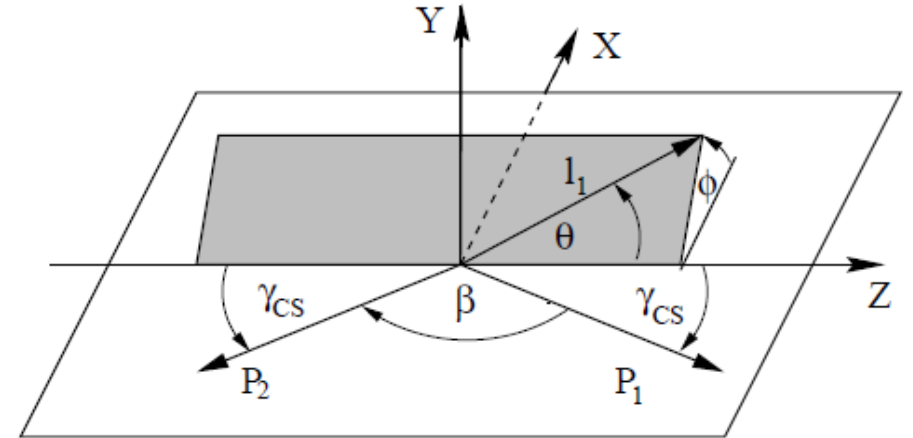
● DØ: 5.0/fb (sub. PRD) arXiv:1104.4590

- Use charge asymmetry in Collins-Soper Frame
- measure $\sin^2 \theta_{eff}^l$ and g_v, g_a for u/d quarks.
- Uncert. on $\sin^2 \theta_{eff}^l$ < LEP all-hadronic
- Dominant uncertainties: Stat, PDFs
 - Could approach world average uncert with CDF+DØ @10/fb.



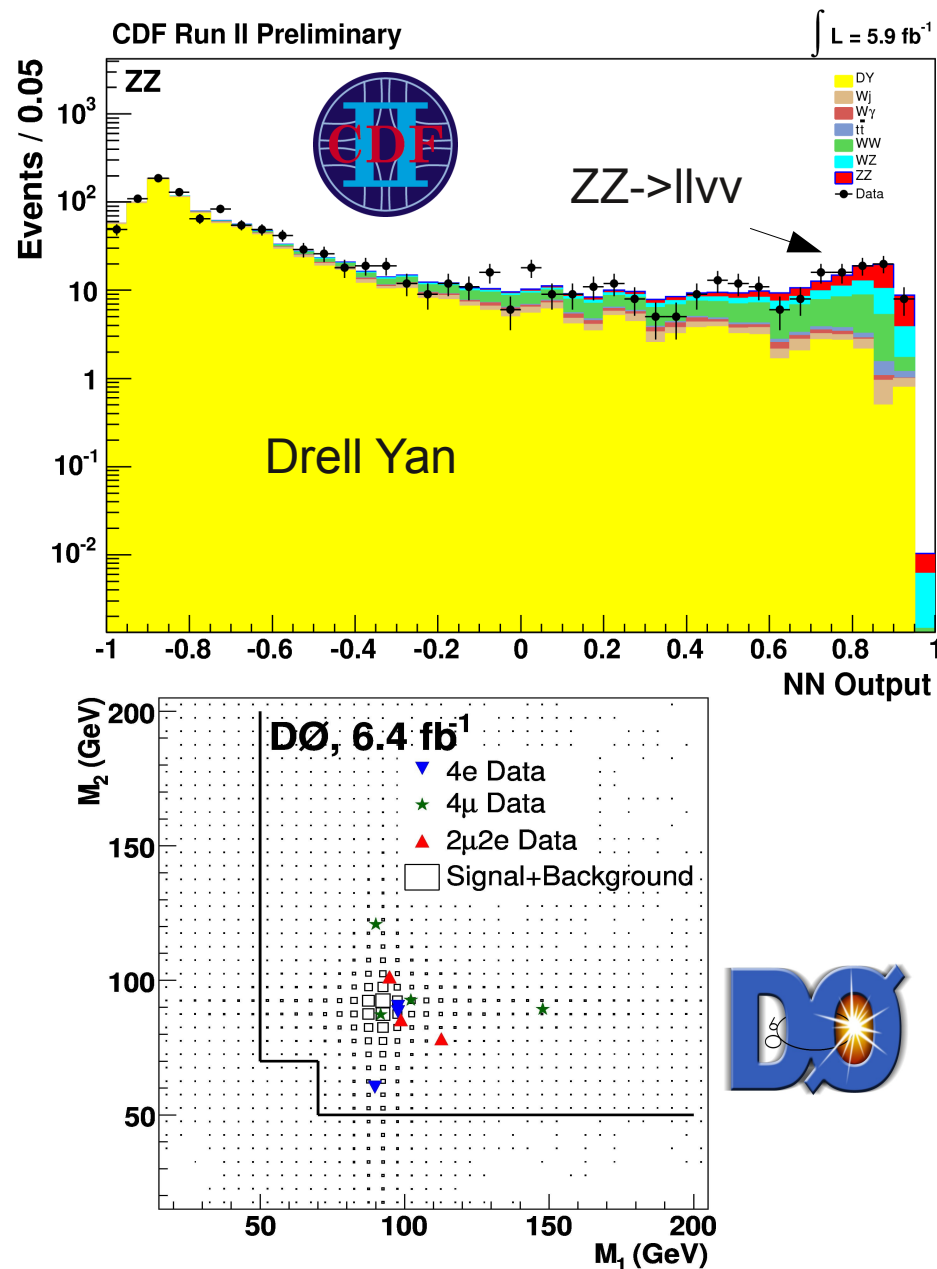
$Z \rightarrow e^+ e^-$ Angular Coefficients

- Possible in general to write the angular distributions of Drell-Yan events in & angular coefficients: A_0 - A_6 .
- Measure differential cross section in PT
- Extract 4 coefficients, compare to SM predictions
- Test Lam-Tung Relation (PRD 18 2447 (1978))
 - Analogous to Callin-Gross
 - $A_0=A_2$, implies gluon is spin 1, vector
 - Consistent with observations



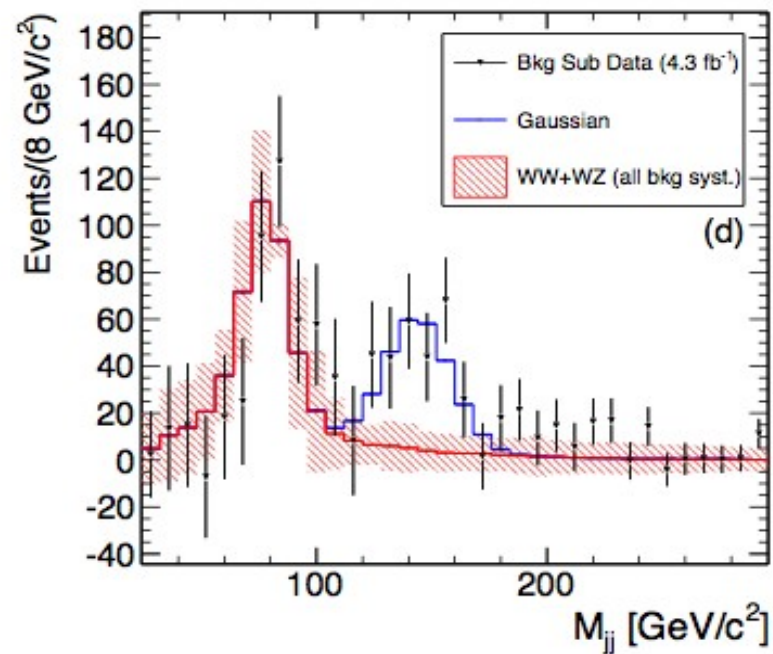
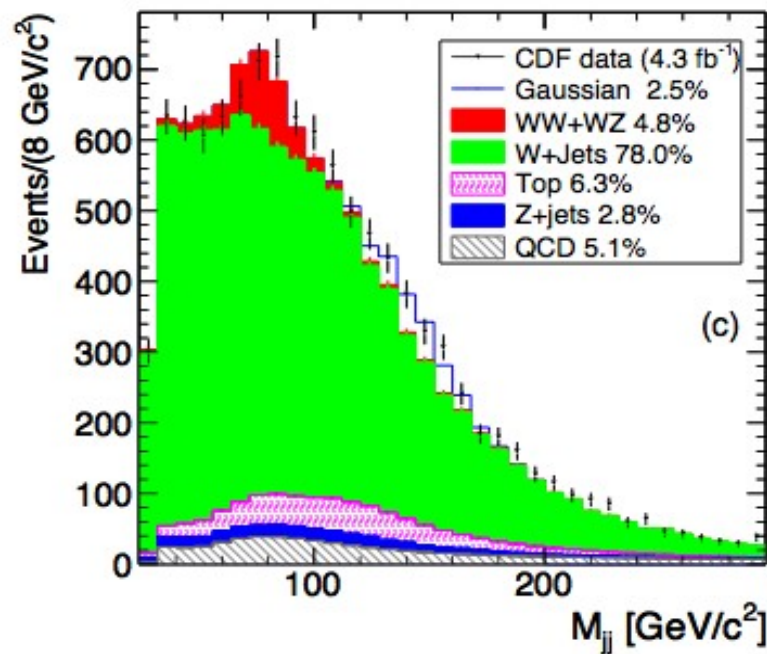
Diboson Production Results

- WW/WZ in all leptonic modes (CDF 6.0/fb, D0 4.1)
- CDF $ZZ \rightarrow ll\nu\nu$ 5.9/fb
 - NN discriminant
 - ZZ XS: $1.45^{+.60}_{-.51}$ pb
 - Stat. uncert \sim syst uncert.
 - NLO $\sim 10\%$
- D0 $ZZ \rightarrow 4l$ (6.4/fb)
 - 10 observed events
 - ZZ XS: $1.40^{+0.43}_{-0.37} \pm 0.14$
- CDF $ZZ \rightarrow 4l$ (5.9/fb)
 - 4 Events
 - $1.7^{+1.2}_{-0.7} \pm 0.2$



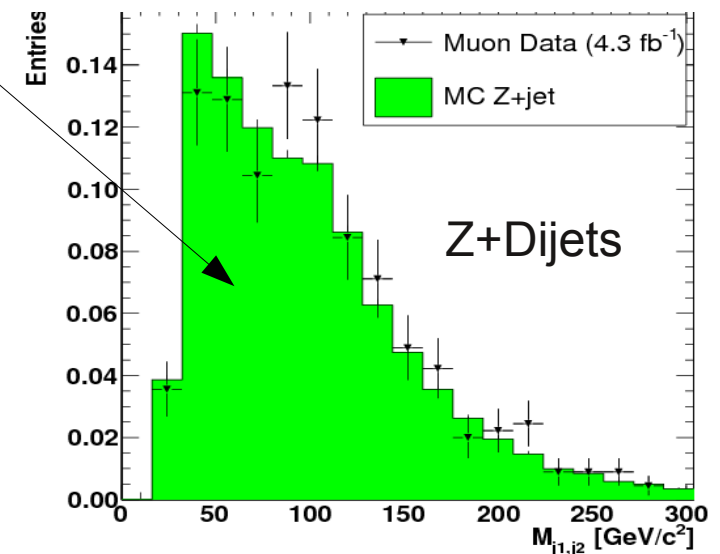
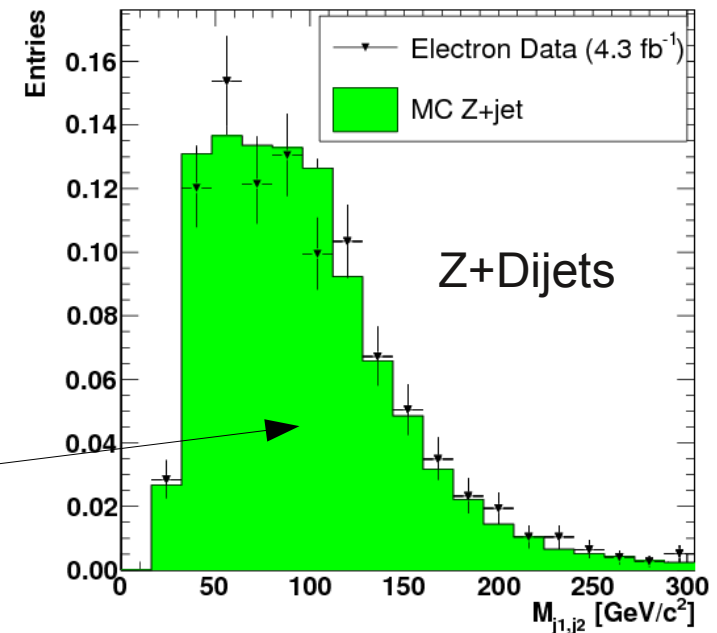
W+jets Invariant Mass Distribution

- In 2010, 4.3/fb WW->lnujj measurement showed localized Data/MC disagreement
- Choice was made to increase jet ET cut from 20→30GeV to diminish systematics. All other aspects of selection/systematics *a priori*.
- Chose to model excess as Gaussian contribution
 - Over all considered systematics/trial factor, Minimum significance: 3.1σ



W+jets Invariant Mass Distribution

- Appearance is suggestive of resonance decaying to jets
 - New physics or unaccounted systematic?
 - Altering selection alters significance, not excess M_{jj} mean
- **Definitely not the SM Higgs**
 - “Cross section” >30x too large, does not favor b-jets
- Shape-Altering systematics
 - Alternate Exponential BG Model
 - Alternate Z+jets data driven BG model
 - PDF, Scale, JES, NLO/LO via MCFM
 - No MC reweighting performed
- **Lots of ongoing work**
 - Awaiting D0 response
 - Alternate generators and matching schemes, reweighting, diagrammatic content
- Lots of supplemental plots and tables:
 - <http://www-cdf.fnal.gov/physics/ewk/2011/wjj/>



Flavor Physics

● Results Presented Here:

- Bs CP violating phase, Mixing Parameters
- Anomalous like sign dimuon charge asymmetry
- Branching Fraction of $B^0 \rightarrow J/\psi f_0(980)$

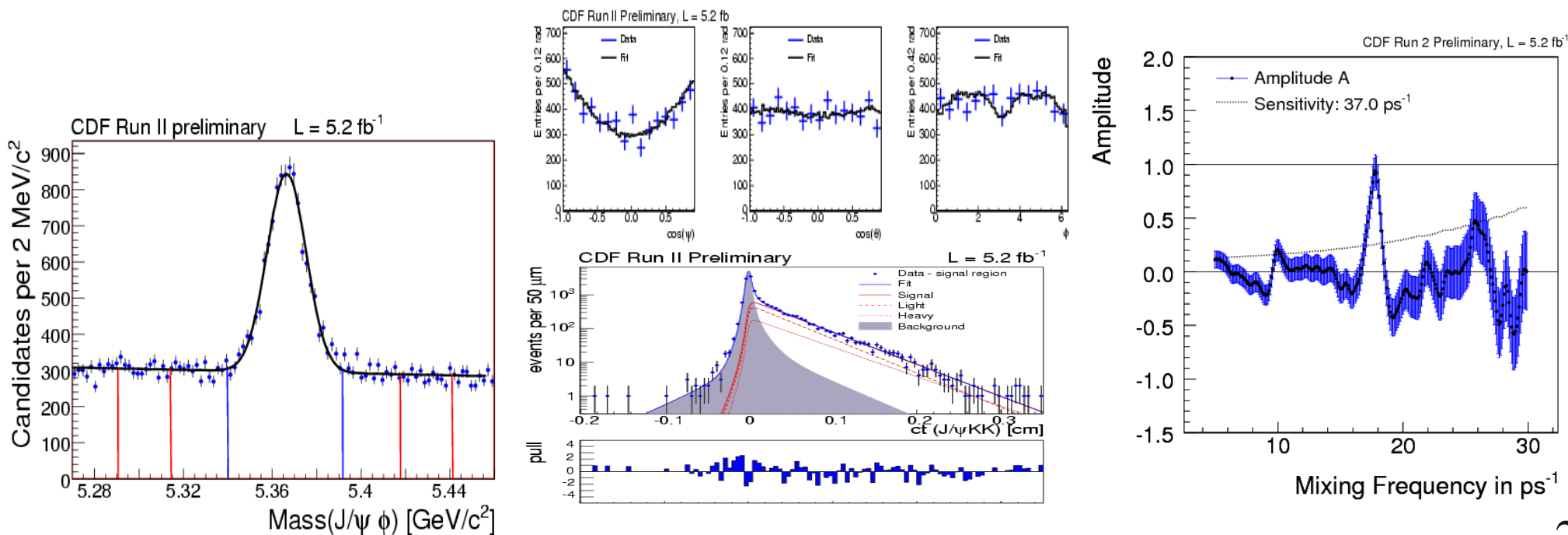
● Other Great Results:

- Observation of $Y(4140)$ in the $J/\psi \phi$ Mass Spectrum in $B^+ \rightarrow J/\psi \phi K^+$
- Measurement of the production fraction times branching fraction $f(b \rightarrow \Lambda_b) \cdot BR(\Lambda_b \rightarrow J/\psi \Lambda)$
- B^+ Lifetime in $B^+ \rightarrow D^0 \pi^+$
- Search for the Rare Decay $D^0 \rightarrow \mu^+ \mu^-$
- Improved measurement of time-integrated CP violation in $D^0 \rightarrow h^+ h^-$ decays
- Measurement of the time-integrated mixing probability of B mesons



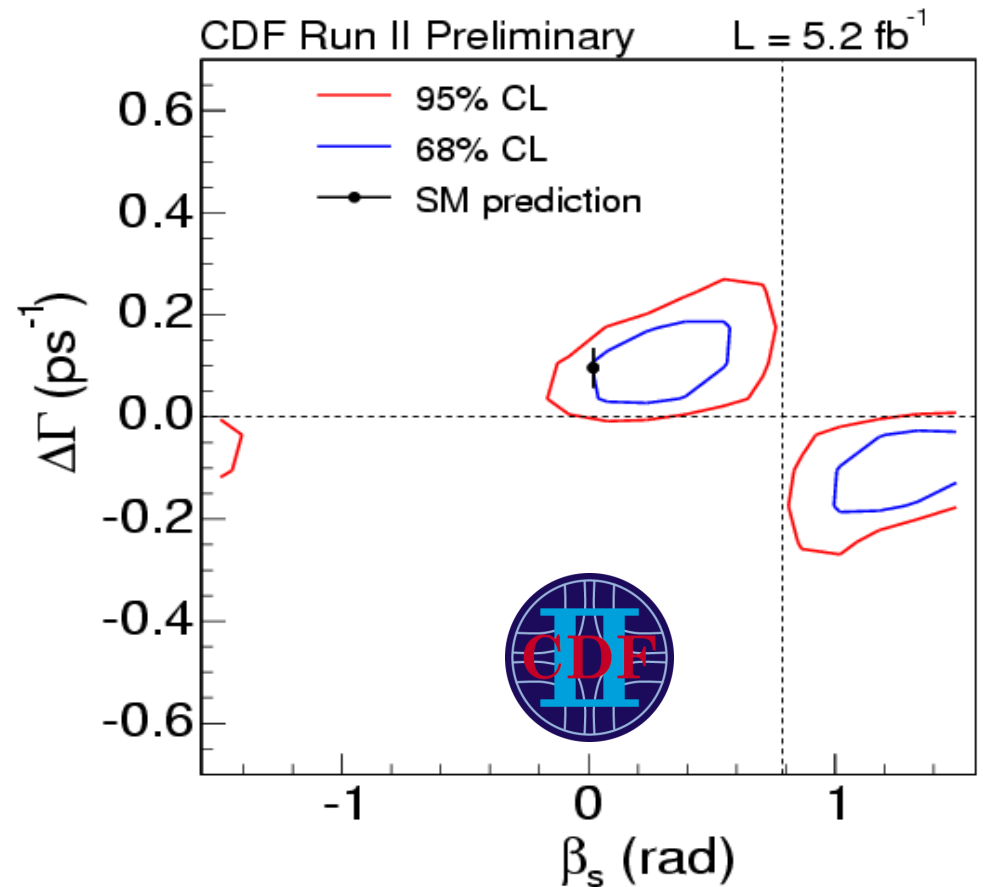
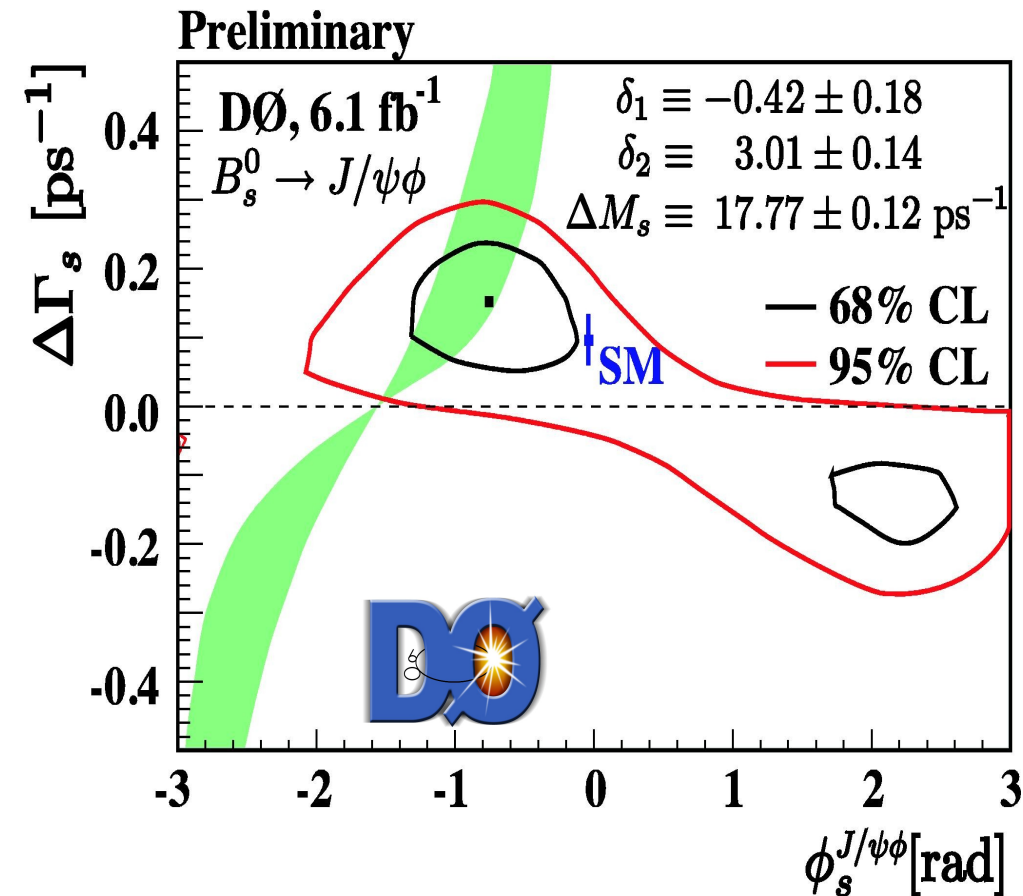
Mixing Parameters in Bs

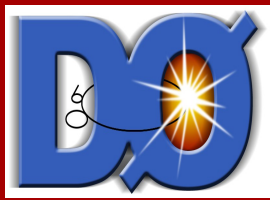
- CDF Update With 5.2/fb, exclusive Bs/ \bar{B} s state id via flavor tagging.
 - Simultaneous fit in Bs mass, angular shapes (CP eigenstate separation), Time dependent decay.
 - Constrain of the S-wave component background in fit.
 - Uses same-side kaon tagger



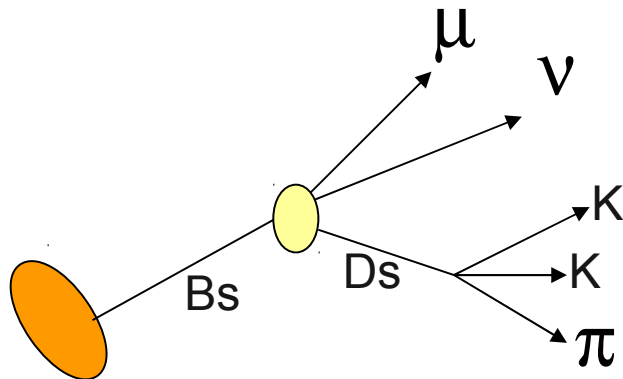
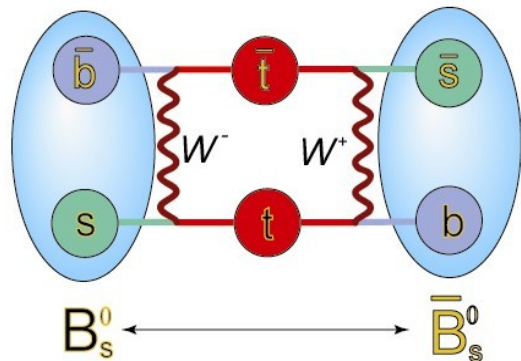
Mixing Parameters in Bs

- Both CDF and D0 results compatible
 - Roughly 1-sigma SM tension in both measurements

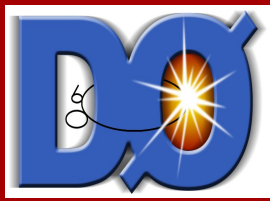




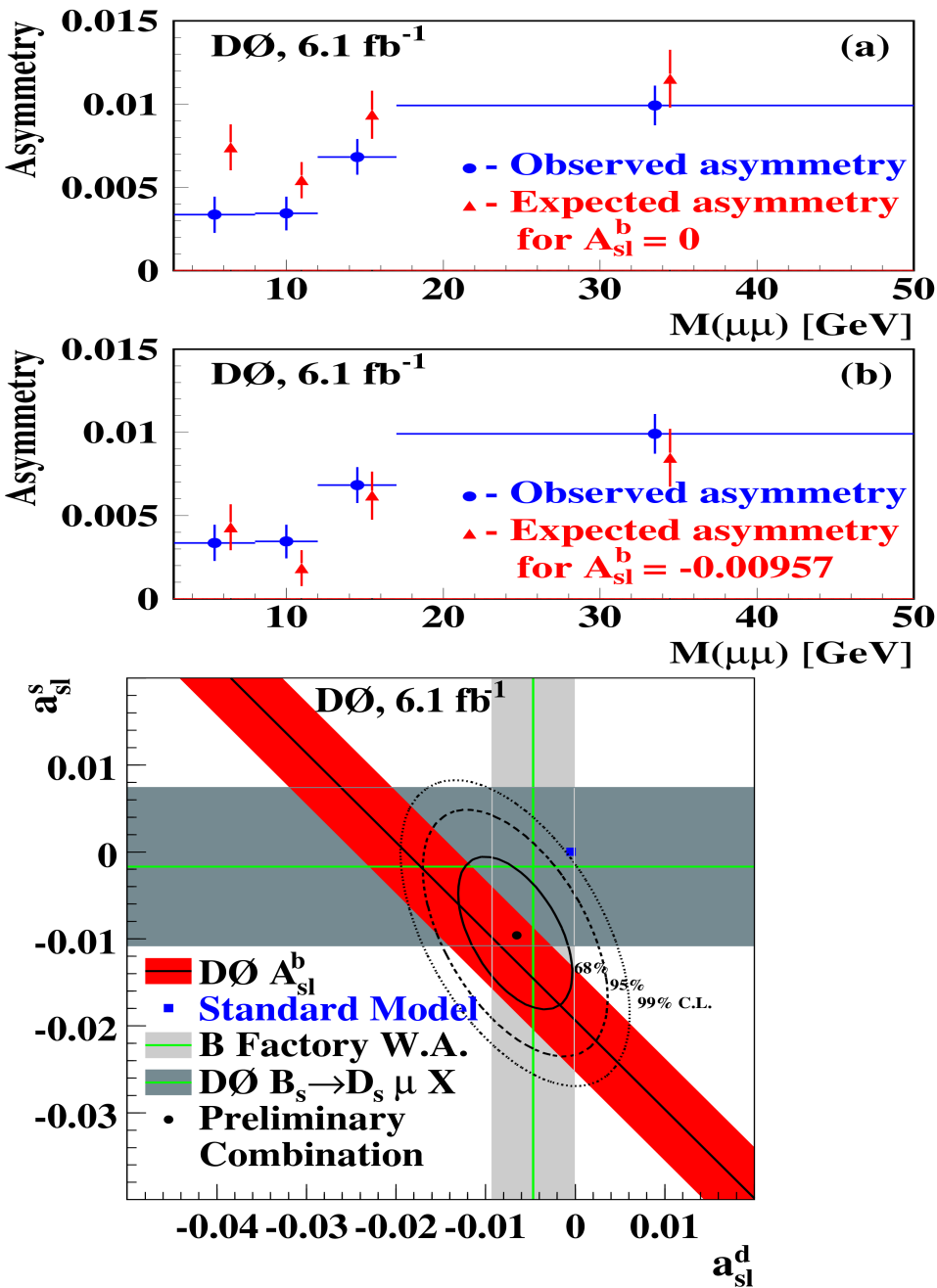
Evidence for Anomalous Like-Sign Dimuon Charge Asymmetry



- B/D Meson mass eigenstates are not flavor eigenstates
 - Oscillations \rightarrow Second order weak interactions
 - Can be used to constrain CKM matrix
- Bd oscillations already measured by D0/CDF
 - D0: Phys. Rev. D 74, 112002 (2006), hep-ex/0609034
- D mixing:
 - CDF: Phys. Rev. Lett. 100, 121802 (2008)
- B0s oscillation frequency/Phase:
 - CDF: Phys. Rev. Lett. 97, 242003 (2006).
 - D0 Phys. Rev. D 76, 057101 (2007), hep-ex/0702030
- D0: Explore B_s^0 mixing via asymmetries:
 - $a_{sl} = [\Gamma(\bar{B} \rightarrow \mu^+ X) - \Gamma(B \rightarrow \mu^- X)] / [\Gamma(\bar{B} \rightarrow \mu^+ X) + \Gamma(B \rightarrow \mu^- X)]$
 - $a_{sl} = A_{sl} = [N^{++} - N^{--}] / [N^{++} + N^{--}]$
- 6.1/fb of data: look for one or two B_0 decays to $\mu + X$
 - 1.5E9 Single muon events
 - 3.7E6 like-sign muon decays

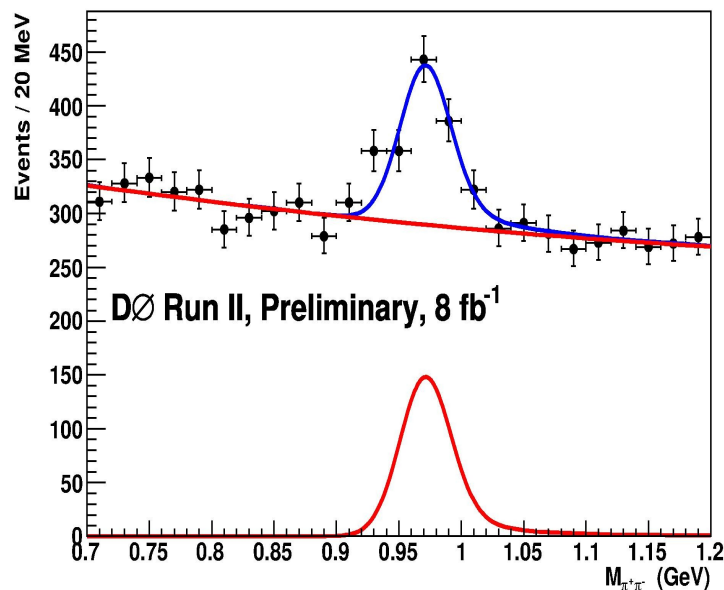
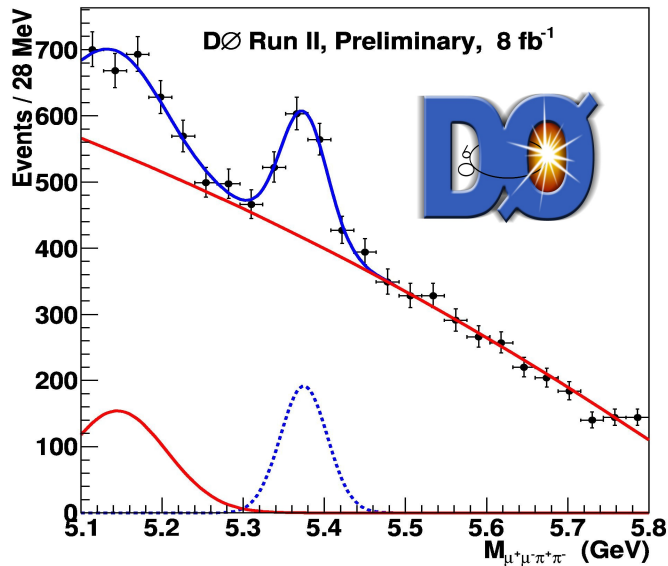


Evidence for Anomalous Like-Sign Dimuon Charge Asymmetry



- No SM deviation in
 - $\Delta\Gamma$, Δm of d or s
- 3.2-sigma deviation from SM charge asymmetry
 - Prefers dimuon to di-antimuon
 - First evidence of anomalous CPV in neutral B mesons
- Periodic reversal of tracker field reduces systematics (D0 only)
- Many separate background asymmetries individually measured

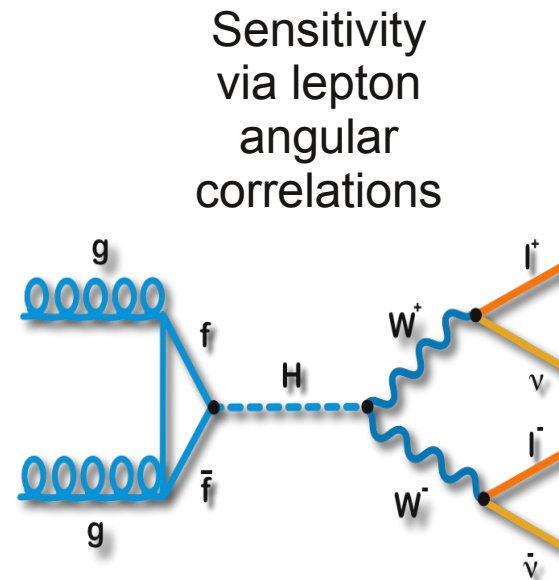
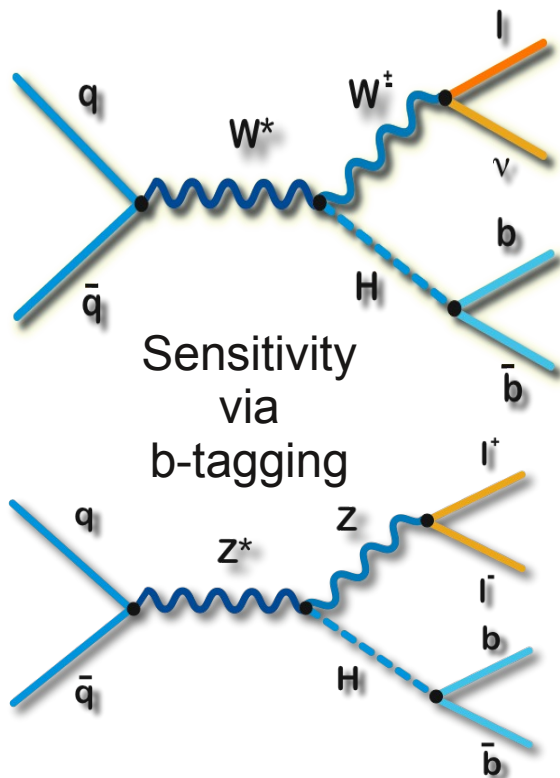
Relative Branching to f0(980)



- D0: Measurement of the **relative branching fraction** of $B_0s \rightarrow J/\psi f_0(980)$, $f_0(980) \rightarrow \pi\pi$ to $B_0s \rightarrow J/\psi \phi$, $\phi \rightarrow KK$
 - Decays of $B_0s \rightarrow J/\psi f_0(980)$ are CP eigenstates
 - Provide more direct measurement of ϕ_s than $J/\psi \phi$
 - Provide complimentary systematics to $J/\psi \phi$
 - Fitting uncertainty on $M_{\pi\pi}$ largest systematic on R
 - $R = .210 \pm .032 \pm .036$

SM Higgs Searches

- ~ 1000 Higgs Events expected to be produced in 10/fb!
- Associated production ($H \rightarrow b\bar{b}$) and direct ($H \rightarrow WW$) modes largest, but searches in many modes contribute
 - CDF+D0 combination



Light Higgs Searches

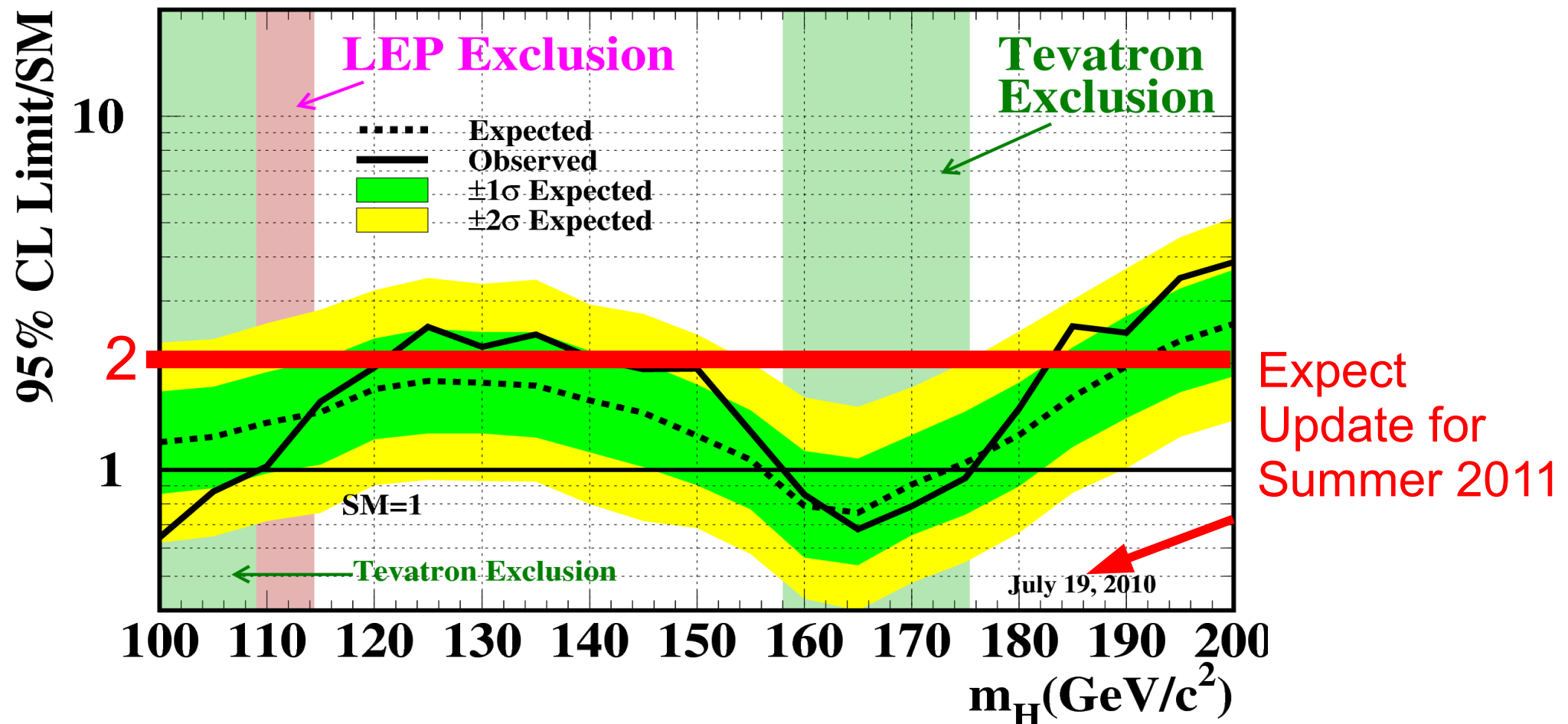
- Sensitivity
at 115 (xSM):

Channel	CDF	D0
$WH \rightarrow lvbb$	3.5	4.8
$ZH \rightarrow \nu\nu bb$	4.0	4.0 Updated
$ZH \rightarrow llbb$	5.5	5.7
$H \rightarrow WW \rightarrow l\nu l\nu$	10.8 Updated	8.6 Updated
$ZH+WH \rightarrow jjbb$	18	19.9
$H \rightarrow \tau\tau$	15 Updated	12.8 Updated
$H \rightarrow \gamma\gamma$	13 Updated	11 Updated

Light Higgs Searches

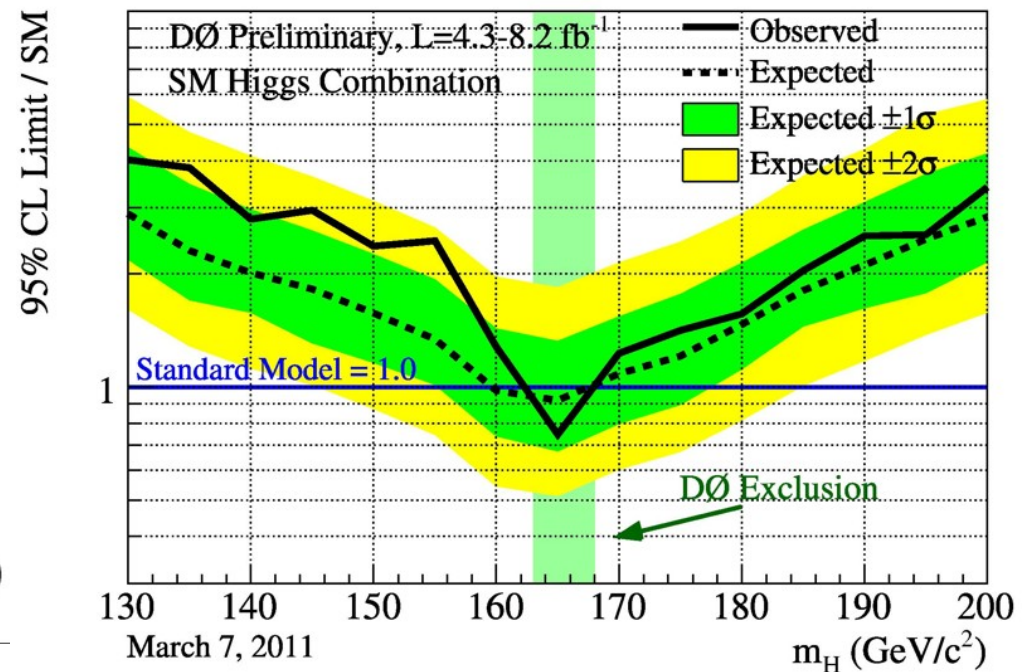
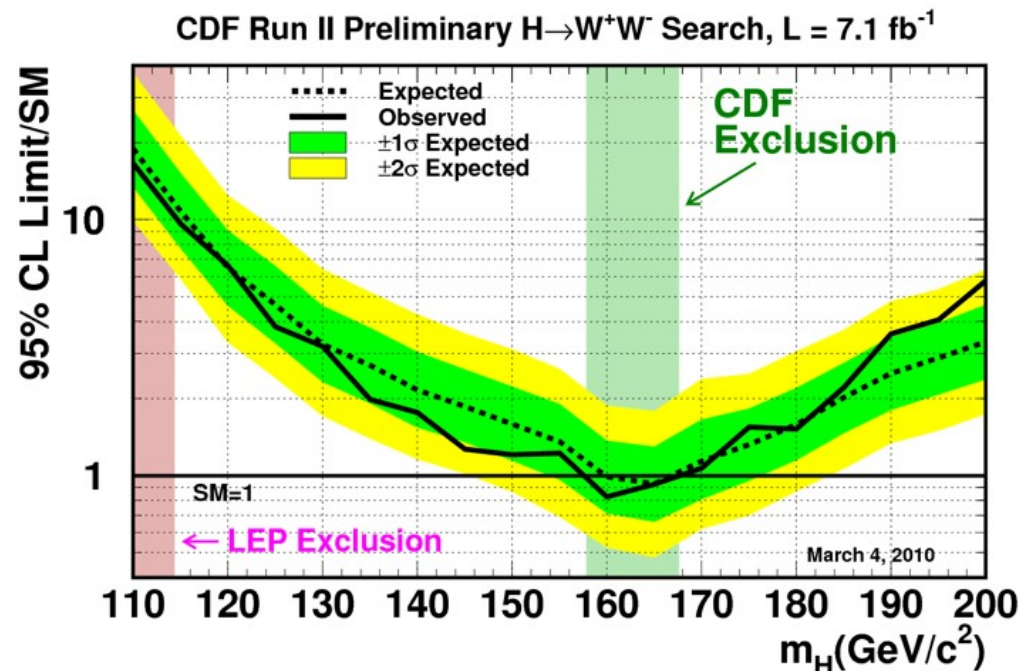
- Expected sensitivity now better than 2xSM for SM Higgs masses below 190 GeV!

Tevatron Run II Preliminary, $\langle L \rangle = 5.9 \text{ fb}^{-1}$

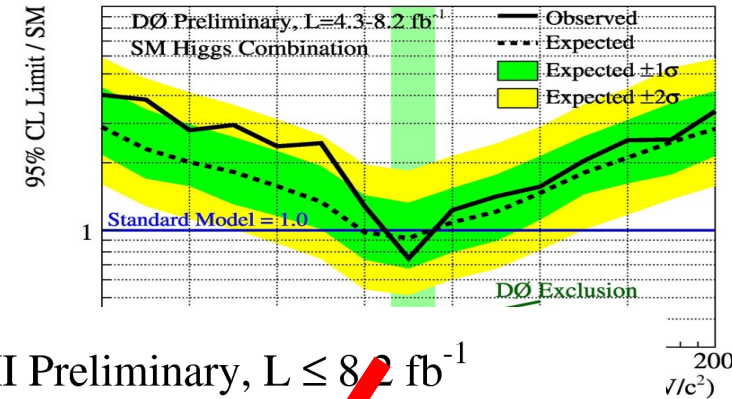
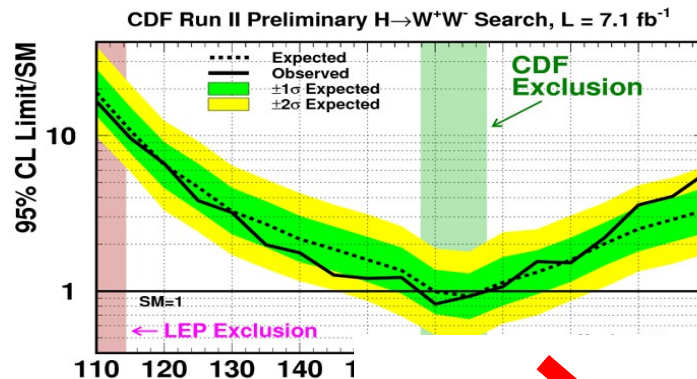


Heavy Higgs Searches

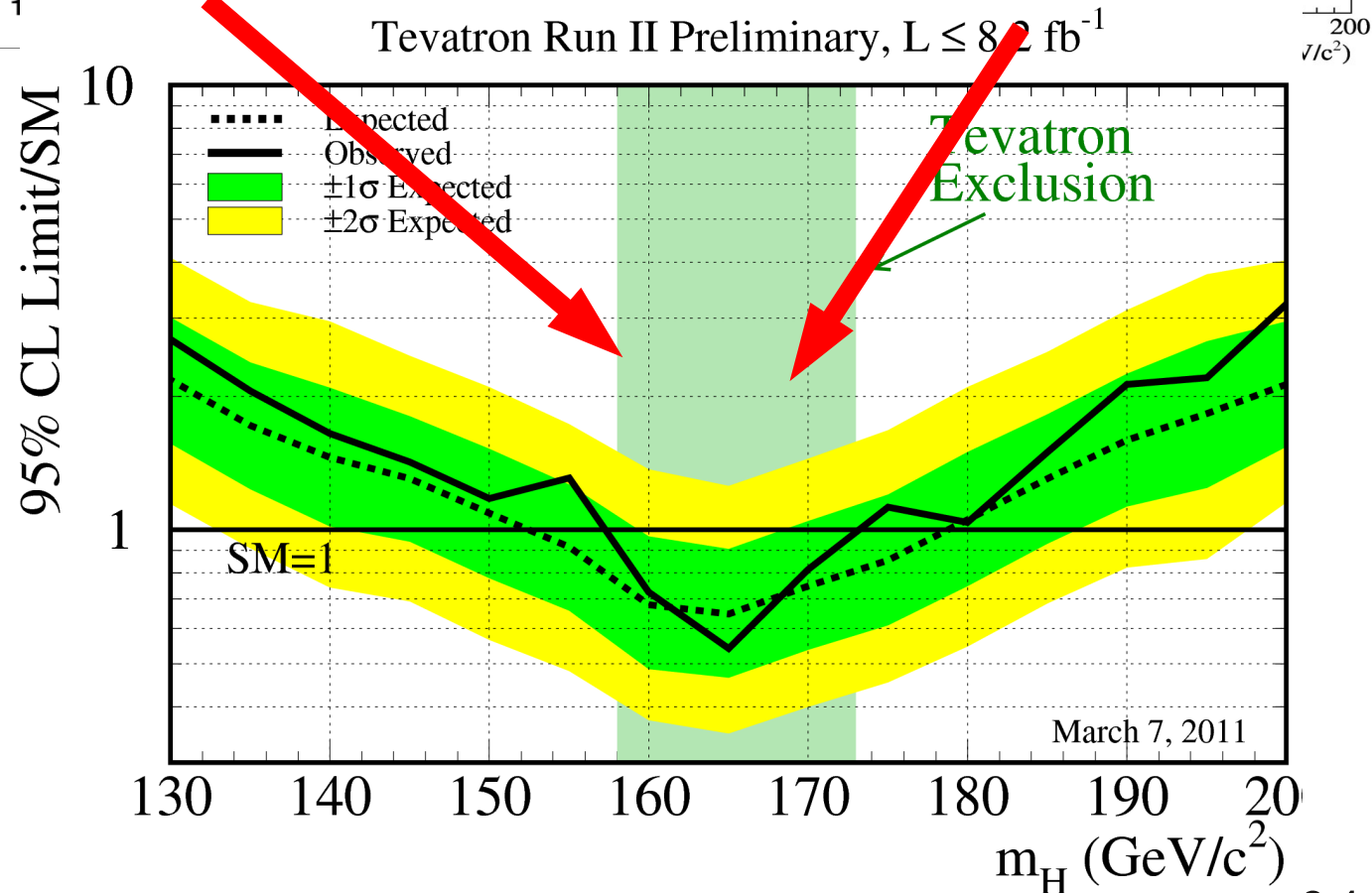
- Now SM Sensitivity at 165 for both experiments!
 - Large datasets ($>7/\text{fb}$)
 - Many low-signal/bg regions, high acceptance
 - Primary background: SM WW



High Mass Higgs Combined Search



- March 2011
- Use correlated uncertainties between CDF/D0
- Exclusion range:
 - [153,179] Exp
 - [158, 173] Obs



Conclusions

- Tevatron has vibrant SM physics program
 - New ways to access QCD (precision QCD!)
 - Exciting hints of large CPV in b-sector
 - Better understanding of the top quarks
 - Large Top AFB signature seen in
 - Both Semileptonic (CDF & D0) and Dileptonic (CDF)
 - New EWK measurements possible with larger datasets
 - W+Mjj Excess: New physics? New systematics?
 - SM Higgs: ~SM Sensitivity at High Mass
 - Low mass <2xSM and gaining

Conclusions

- For additional results see

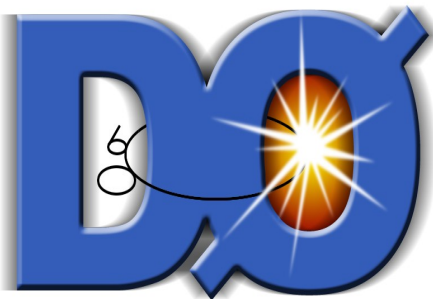
- http://tevnphwg.fnal.gov/results/SM_Higgs_Winter_11/
- <http://www-cdf.fnal.gov/physics/new/hdg/Results.html>
- <http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.html>

Conclusions

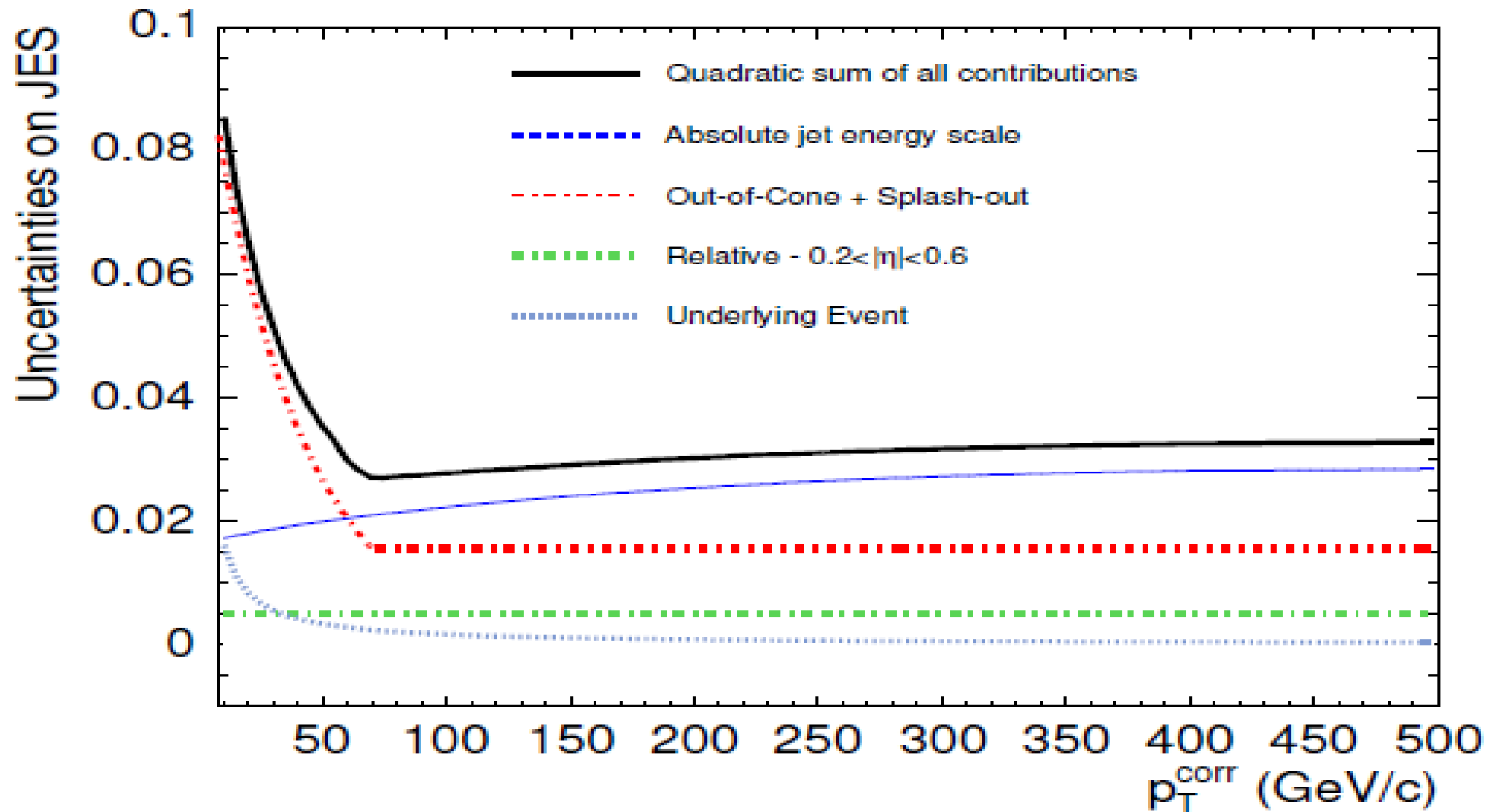
- Tevatron has vibrant SM physics program
 - New ways to access QCD (precision QCD!)
 - Exciting hints of large CPV in b-sector
 - Better understanding of the top quarks
 - Large Top AFB signature seen in
 - Both Semileptonic (CDF & D0) and Dileptonic (CDF)
 - New EWK measurements possible with larger datasets
 - W+Mjj Excess: New physics? New systematics?
 - SM Higgs: SM Sensitivity at High Mass
 - Low mass $< 2 \times \text{SM}$ and gaining

Thank you for your attention

Questions?



● JES



● PDFs

ArXiv:1101.1300

NNPDF2.1 dataset

